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(Summary)

AN INVESTIGATION OF THE INTERCHANGE OF TENSILE CREEP FOR COMPRESSIVE CREEP

Part 1. Types 2024-T4 and 1100-0 Aluminum

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MARCH 1956

[redacted]

WRIGHT AIR DEVELOPMENT CENTER

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MATERIALS LABORATORY
CONTRACT No. AF 33(616)-2738
PROJECT No. 7360

WRIGHT AIR DEVELOPMENT CENTER
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UNITED STATES AIR FORCE
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

Carpenter Litho & Prtg. Co., Springfield, O.
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FOREWORD

This report was prepared by Battelle Memorial Institute, Columbus, Ohio, under Contract No. AF 33(616)-2738. The investigation was initiated under Project No. 7360, "Materials Analysis and Evaluation Techniques", Task No. 73605, "Design and Evaluation Data for Structural Metals", as a project of the Materials Laboratory, Directorate of Research, Wright Air Development Center, with Mr. E. L. Horne acting as project engineer. This report covers work performed during the period 15 December, 1954, to 15 December, 1955.

The authors wish to acknowledge the guidance of Dr. C. H. Lorig who served in the capacity of Technical Director.

ABSTRACT

Aluminum 1100-0 and aluminum alloy 2024-T4 were subjected to tension- and compression-creep testing at varying stress levels and temperatures. Creep data were compared to establish whether significant differences existed between tension and compression behavior. Room-temperature and elevated-temperature static properties of each material were obtained. Metallographic and hardness studies were used to supplement the results of creep and static tests. Test equipment and test techniques were developed which permitted creep measurements approaching 10 microinches per inch in sensitivity and ± 25 microinches accuracy. Data obtained on 2024-T4 and 1100-0 aluminum in all instances indicated greater creep resistance in compression. Differences in tension- and compression-creep strain decreased with increasing temperatures. Results indicated that a reversal in the interchange of 2024-T4 may take place between 375°F and 450°F and that interchange may be a temperature-dependent phenomenon.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

M. R. WHITMORE
Technical Director
Materials Laboratory
Directorate of Research

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INTRODUCTION

It has been common practice in evaluating mechanical properties at elevated temperatures to use tensile-creep data as a basis for design in both tensile- and compressive-stress situations. Tensile testing has been preferred over compressive testing because tensile tests are easier to perform and because tensile data are more readily available. The exclusive use of tensile-creep data, of course, requires the assumption that tensile- and compressive-creep behavior are the same. Although this is a very useful assumption, it has not been established as valid.

One of the purposes of the investigation summarized by this report was to examine the validity of this assumption for 2024-T4 and 1100-0 aluminum.* In a program of this type, particular care must be exercised in the execution of the experimental work. Lack of attention to detail may give rise to conditions that may either weaken or completely invalidate the conclusions derived from the comparisons. For this reason, considerable effort was devoted to the development of specimens, test equipment, and test procedures. These efforts are, therefore, considered a major part of the program to be described. With this in mind, the test results obtained during the period of research covered were intended to serve two ends. One was to provide an opportunity to "check out" the equipment and procedures evolved. The second was to provide a set of data that could serve as a guide for the design of future experiments that could in turn provide an insight into the factors that control tensile- and compressive-creep behavior.

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* Formerly designated as 24S-T4 and 2S-0, respectively.

A review of the literature indicates that the substitution of tensile-creep data for compressive-creep data can be either conservative or nonconservative. Work by Sully, Cole, and Willoughby[1] on a nickel-chromium alloy indicated that the resistance to creep in compression was less than that in tension. This behavior was also observed by Schwope, Smith, and Jackson[2] on several commercial coppers.

Other work has indicated, however, that it is possible for the resistance in tension to be less than that in compression. Carlson and Manning[3], for example, observed this behavior for the aluminum alloy 2024-T4.

Probably the most extensive single source of comparisons between tensile- and compressive-creep behavior is given in a paper by Yerkovich and Guarnieri[4]. They present data for materials of three classifications: wrought metals, castings, and metal-ceramic composites. A summary of their tentative conclusions is as follows:

1. Wrought materials displayed less resistance to creep in compression than in tension. This was attributed to the possible presence of preferred orientations and residual stress patterns acquired during fabrication.
2. Cast materials were indicated as having insignificant differences in resistance to creep. The explanation for this behavior was related to the fact that directionality of properties due to working was not present.
3. Metal-bonded ceramics had a superior resistance to creep in compression. This behavior was related to the essential difference in response that may

occur for a material that is in essence heterogeneous (hard particles dispersed in a metallic binder). Since such materials are brittle or weak in tension, the effect of stress raisers may be expected to result in a greater weakening in tensile loading than in compressive loading.

Before commenting on these results, it should be noted that the authors emphasized that the above conclusions were based on limited data for each material. The behavior explanations advanced were tentative, and it is quite possible that they were, at least in some instances, oversimplifications of the actual behavior.

In particular, attributing the difference in tensile and compressive behavior to orientation or directional effects seems unsound. Although directional effects are certainly often present after working, the resulting differences in behavior usually observed are for different directions of loading. The loading for the tests considered (tensile and compressive creep) was unidirectional. The primary difference, then, for slip on a given plane exists in the force normal to the slip plane. This difference is usually assumed to have no effect on slip.

The reference to residual stress patterns is probably more sound. It is probable, in fact, that microresidual stresses, and perhaps substructure formation, as well as macroresidual stresses can influence the creep behavior and result in differences in the tensile and compressive responses. The fabrication process and the subsequent heat treatments no doubt can result in various possible behaviors. It is probable, in fact, that different histories may even result in reversals of behavior. That is, for one process, the resulting resistance to creep in tension may be greater, whereas for another process, the resistance in compression may be greater. This reversal can be observed in static behavior, of course, and it is attributed to the Bauschinger effect.

The effect of prior working or prestrain on tensile-creep behavior has been studied quite extensively recently[5,6,7,8]. In all instances, the presence of prestraining had an effect on the subsequent creep behavior. Unfortunately, however, no compressive-creep data were obtained in these studies.

Since it appears likely from the above discussion that variations in fabrication history may introduce and perhaps control differences in tensile- and compressive-creep behavior, it is felt that a study of the effects of prestrain should be included in future work.

TEST EQUIPMENT AND TEST APPARATUS

The specific objectives of this research were stated in the introduction of this report. The development of test equipment and methods was carried out in an attempt to meet these objectives.

Statistical Selection of Test Specimens

In the selection of materials for this investigation, it was specified that the materials be obtained from the same lot or heat. This was done to promote homogeneity of test material from specimen to specimen. However, complete homogeneity is impossible, even within a given lot. Certain unavoidable variations can be expected. The exact magnitude of these variations cannot easily be known at the outset of such an investigation as this. So long as the possibility exists that these factors might affect the data, their influence should be considered. Such unknown factors can result in false conclusions when they occur in an ordered or nonrandom way. If they occur in a random way, that is, if they can be expected to have a comparable effect upon every phase of a research program, their effect may be discounted.

As a result, a statistical program was set up for selecting specimens so as to randomize the possible effects upon test data of unknown variations in history (chemical and physical). The first step in this process was the selection of 6 inches as the length of the material unit. Only one specimen was machined from each material unit. The total length of rod obtained of each material was then divided into 6-inch lengths. A maximum of 352 material units (352 specimens) of each material was deemed sufficient for completing the program. The 6-inch lengths were numbered consecutively from 1 to 352 along the rod and progressing from rod to rod. Then a total of 352 random, 5-digit numbers was selected from a table of random numbers(9). These numbers were then ordered according to increasing magnitude.* This randomized the order of their selection. The resulting randomized set of 352 numbers was then used for the selection of material units of 1100-0 aluminum. The specimens corresponding to the first 16 random numbers were set aside for the fabrication of tension specimens of the 1100-0 aluminum. Those material units corresponding to the next 16 random numbers were set aside for compression specimens. The remainder were reserved to be made into creep specimens. The various specimens were tested in the order of their occurrence in the list of random numbers. Specimens fabricated from 2024-T4 were selected in the same manner with the exception that the selection started with the last random number in the list and worked backwards up the list. The use of this statistical technique for random selection should have eliminated the possibility of unknown factors in the history of the materials influencing the comparison of test data.

* An IBM system was used for carrying out this operation.

Following the division of the stocks of the two test materials into material units, a series of hardness surveys was conducted on random material units of both materials in an attempt to evaluate the uniformity of the as-received materials.

Three hardness readings were made along the surface of each of 48 random material units selected from each material. Rockwell B hardness readings were taken on the 2024-T4 alloy, while the relative softness of the 1100-F aluminum required the use of the Rockwell H scale. These surveys yielded the following hardness limits:

Material	Hardness Scale	Mean Hardness	Standard Deviation
2024-T4 Aluminum Alloy	Rockwell B	80	3
1100-F Aluminum	Rockwell H	71	2

When comparing the hardness of these two materials, it should be pointed out that 87.0 Rockwell H corresponds to 0 Rockwell B and that a change of 1.0 Rockwell H is equivalent to a change of the order of 3.0 Rockwell B. These tests would seem to indicate that the lots of materials received were fairly uniform.

Specimen Designs

Figure 1 contains the designs of the specimens used in carrying out this investigation. In the case of the 2024-T4 alloy, these three specimens were designed to have the same gage section, cross section, surface area, and volume and to have a 2-inch gage length to facilitate accurate strain measurement. In the case of the 1100-0 aluminum, the length of the creep specimen was shortened to reduce the possibility of buckling during compression-creep testing. The creep specimen in Figure 1 was designed so that it could be used for both tension- and compression-creep testing. This should have

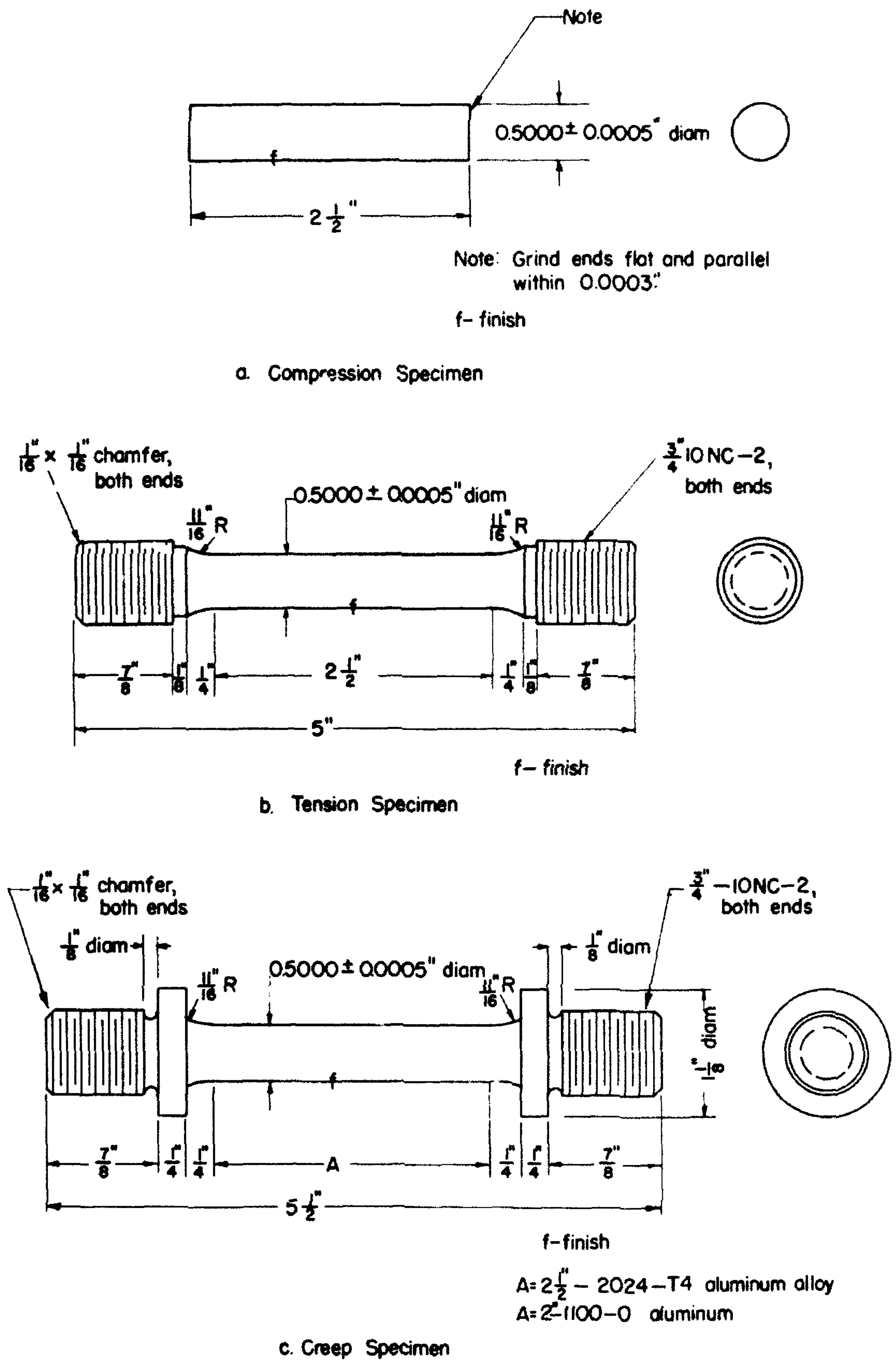

FIGURE 1. SPECIMEN DESIGNS

eliminated any effects that size and shape may have had on the final comparisons of tension- and compression-creep data. The gage sections of all specimens were finished in the same manner to eliminate differences in surface condition. In addition, all three specimens were designed so that their gage section would be machined from the center of the rod.

Test Equipment

Prior to the initiation of this investigation, an evaluation was made of the various equipment and techniques required for the testing of aluminum alloys at room and elevated temperature. No special equipment was required for the static-tension and static-compression testing at room temperature of either material. Specimens were loaded in a standard hydraulic testing machine and strains were obtained by means of SR-4-type strain gages.

For the testing of these two materials at elevated temperatures, equipment already available at Battelle was employed. The fabrication of special equipment was not required. Loading was obtained, as in the room-temperature tests, by means of hydraulic testing machines. Since the maximum temperature at which either of these materials was to be tested was less than 400°F, Bakelite, Type AB-3, SR-4 strain gages were used for strain measurement. Type AB-3 gages were used in all elevated-temperature static tests because their gage factor was known to remain constant up to a temperature of at least 400°F[10].

With the exception of the static-tension tests at 300°F on the 2024-T4 aluminum alloy, all static tests at elevated temperatures were carried out in a large Hevi Duty electric oven. This oven was constructed so that it could be rolled onto the bed of a standard hydraulic testing machine. The oven was equipped with an internal circulating fan and baffled so that a very even temperature could be maintained throughout the oven. This oven was constructed to permit the application of loads through holes in its roof and floor. Static-tension tests were conducted by inserting the grips through these holes and connecting them to the fixed and moving heads of the testing machine. Dummy strain gages used for temperature compensation of strain were mounted on a 2024-T4 aluminum specimen of the same design but of a different lot of material.* This specimen was wired to one of the tensile grips. Exploratory experiments conducted on this apparatus indicated a maximum total temperature difference throughout the oven of less than $3^{\circ}F$ at $300^{\circ}F$ and $375^{\circ}F$. The static-tension tests at $300^{\circ}F$ on the 2024-T4 aluminum alloy were conducted in a closed tube, wire-wound furnace which was supported between the heads of the testing machine. This furnace permitted the external adjustment of the temperature distribution along its length. It was capable of producing a temperature distribution of $300^{\circ}F \pm 2^{\circ}F$ over the 2-inch gage length of these specimens.

In the compression tests, specimens were placed in a subpress of the type recommended by ASTM Method B-9-46-T and similar to the subpress shown in Figure 30 of WADC Technical Report 52-251, Part 1. The entire assembly, specimen, subpress, and dummy gages, was placed inside the Hevi Duty electric oven on a circular platten.

Before initiating the creep tests, an evaluation was made of the various systems and techniques for the measurement of creep strain. Of these systems, that employing the platinum-strip extensometer(11) was deemed most capable of attaining the accuracy required by this investigation. This type of extensometer, which has been used for some time at Battelle for creep measurements, can be wholly enclosed within the furnace. Special clamps were required to fasten these strips to the creep specimen.

* Material from Battelle's stock.

Figure 2 is a photograph showing one of these strip extensometers mounted on a creep specimen by means of the special clamps. Figure 2 also shows a special jig used for positioning and accurately spacing the gage clamps. The base of the jig in Figure 2 consists of two parts separated by a compressible material. This type construction permitted the adjustment of the end blocks which positioned the gage clamps. As a result, it is estimated that the gage clamps could be located to give the proper 2-inch gage length within 0.003 inch. In addition, this mounting jig facilitated obtaining parallelism of the extensometer surfaces.

Figure 3 is a photograph of two platinum-strip extensometers (at 20X). Creep measurements were made by measuring the relative movement of reference marks on the strip. The measurement of this movement was made by means of a specially designed filar micrometer microscope.* This micrometer microscope had a sensitivity of movement of 0.00002 inch, or 10 microinches per inch on a two-inch gage length. This microscope employed a 5X objective and a 10X eyepiece which were mounted a fixed distance apart. The eyepiece was fitted with a travelling set of cross hairs actuated by a filar micrometer screw. This microscope was fitted with a simple relay lens which enabled focusing upon an object approximately 5 inches from the forward end of the microscope. Light was furnished by an illuminator mounted in the tube of the relay lens.

The extensometer at the right of Figure 3 is the extensometer normally used at Battelle for creep measurements. The strip at the left is the extensometer developed for this investigation. The reference marks on the old extensometer were made by scribing lines with a sharp instrument. However, the width of the lines and the width of the reference intersections of the old extensometer were of an order of magnitude that was prohibitive

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* Obtained from the Gaertner Scientific Corporation of Chicago, Illinois.

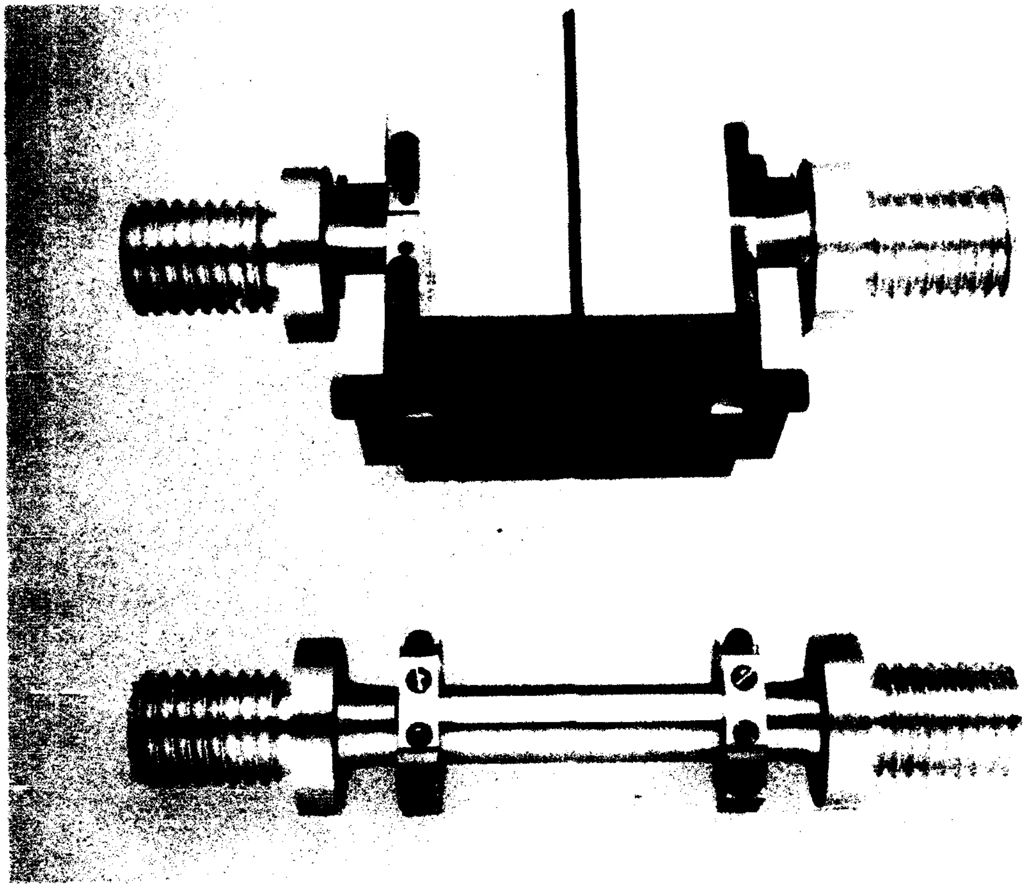

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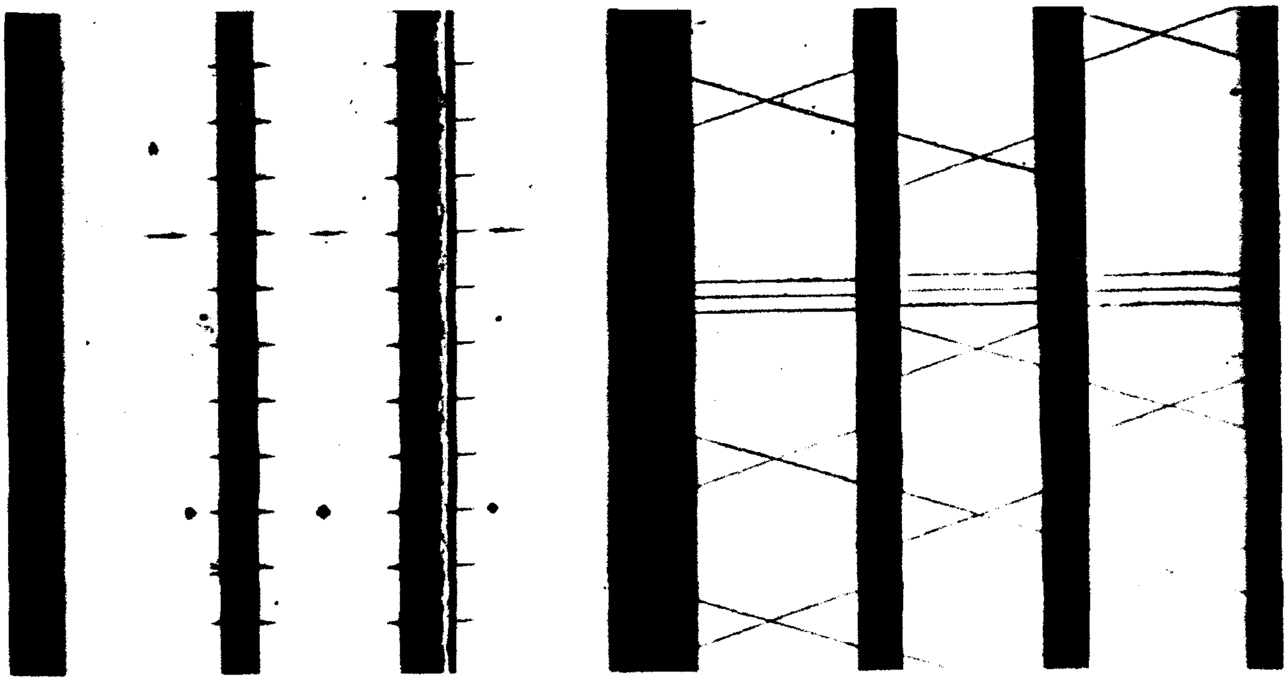
FIGURE 2. CREEP SPECIMEN SHOWING PLATINUM-STRIP EXTENSOMETER AND JIG FOR ACCURATELY LOCATING AND MOUNTING EXTENSOMETER



20X

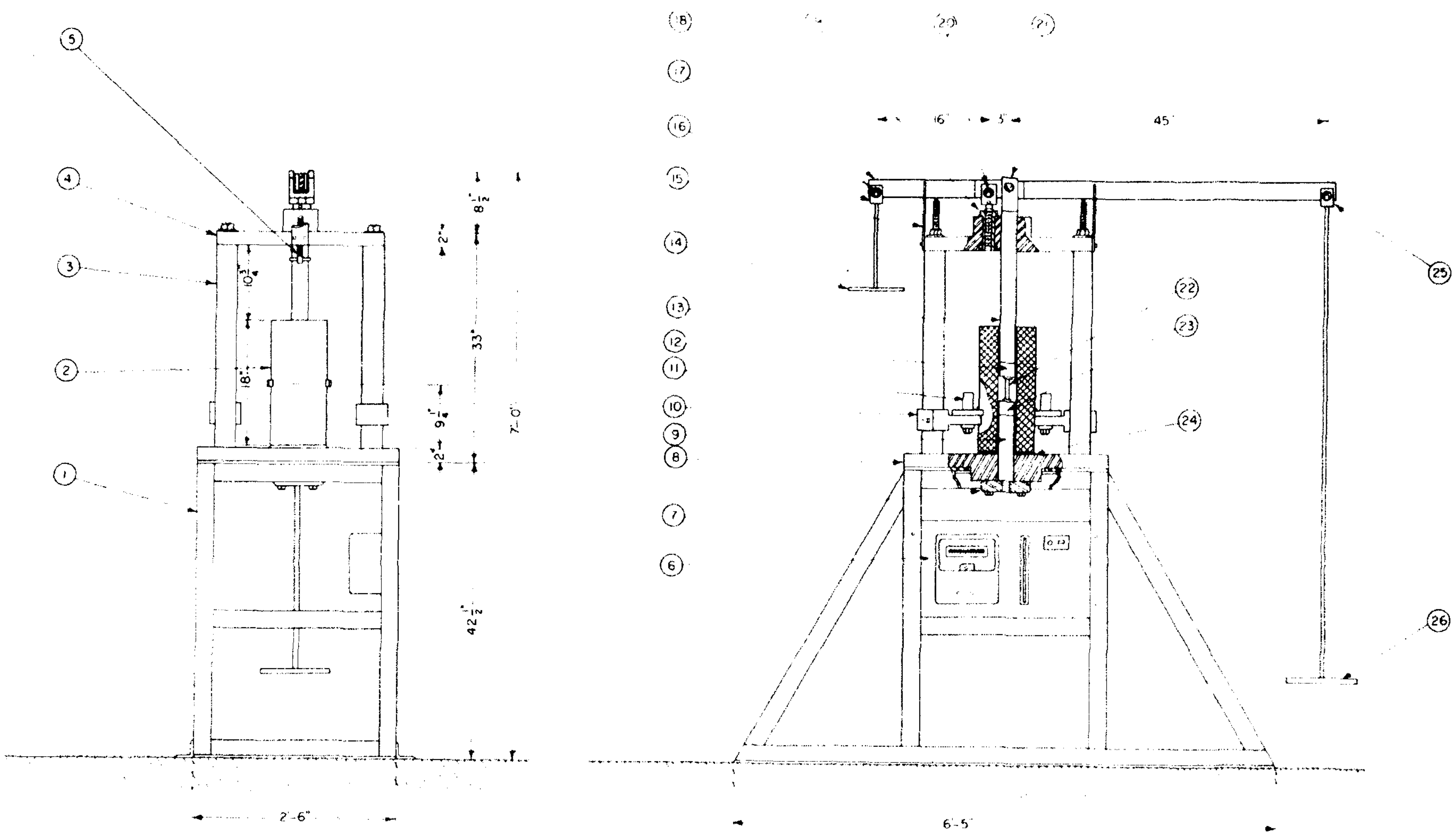
N20233

FIGURE 3. PLATINUM-STRIP EXTENSOMETERS FOR MEASURING CREEP DEFORMATIONS: LEFT - NEW, RIGHT - OLD

to this investigation. The new extensometer at the left in Figure 3 was developed in an attempt to obtain as fine and distinct reference marks as possible. The reference marks on the new extensometer consist of microhardness indentations made with a Knoop diamond. The reference marks on this new extensometer were spaced 400 microns apart.

In order to carry out the compression-creep testing of the investigation with the desired accuracy, a special creep-testing unit was designed. Figure 4 is a schematic drawing of this unit. Figure 5 is a photograph of the completed unit. This unit was designed to permit the use of a closed furnace. Such a furnace was deemed necessary to obtain the desired temperature control. The furnace was fitted with two windows through which the creep measurements could be made. In addition, the unit was designed to permit raising the furnace while the specimen was being inserted and aligned. The furnace is shown in the raised position in Figure 5. Furthermore, this unit was designed with a variable adjustment plunger which permitted initial alignment of the specimen at room temperature and final alignment at test temperature. Figure 5 also shows the filar micrometer microscope used for making the creep measurements.

The creep unit shown in Figures 4 and 5 was designed with a lever-arm ratio of 16 to 1. To insure the accuracy of this ratio, considerable care was taken to position the knife edges accurately. However, following the completion of construction of the unit, tests were conducted to check the accuracy of the lever-arm ratio. In these tests (conducted at room temperature), strain gages were placed on a dummy creep specimen and the axial strain of this specimen calibrated against the load determined from a Baldwin-Southwark universal testing machine. This dummy specimen was then placed in the creep unit and loaded. The strain thus produced in the specimen was then checked against the calibration. Repeated calibrations

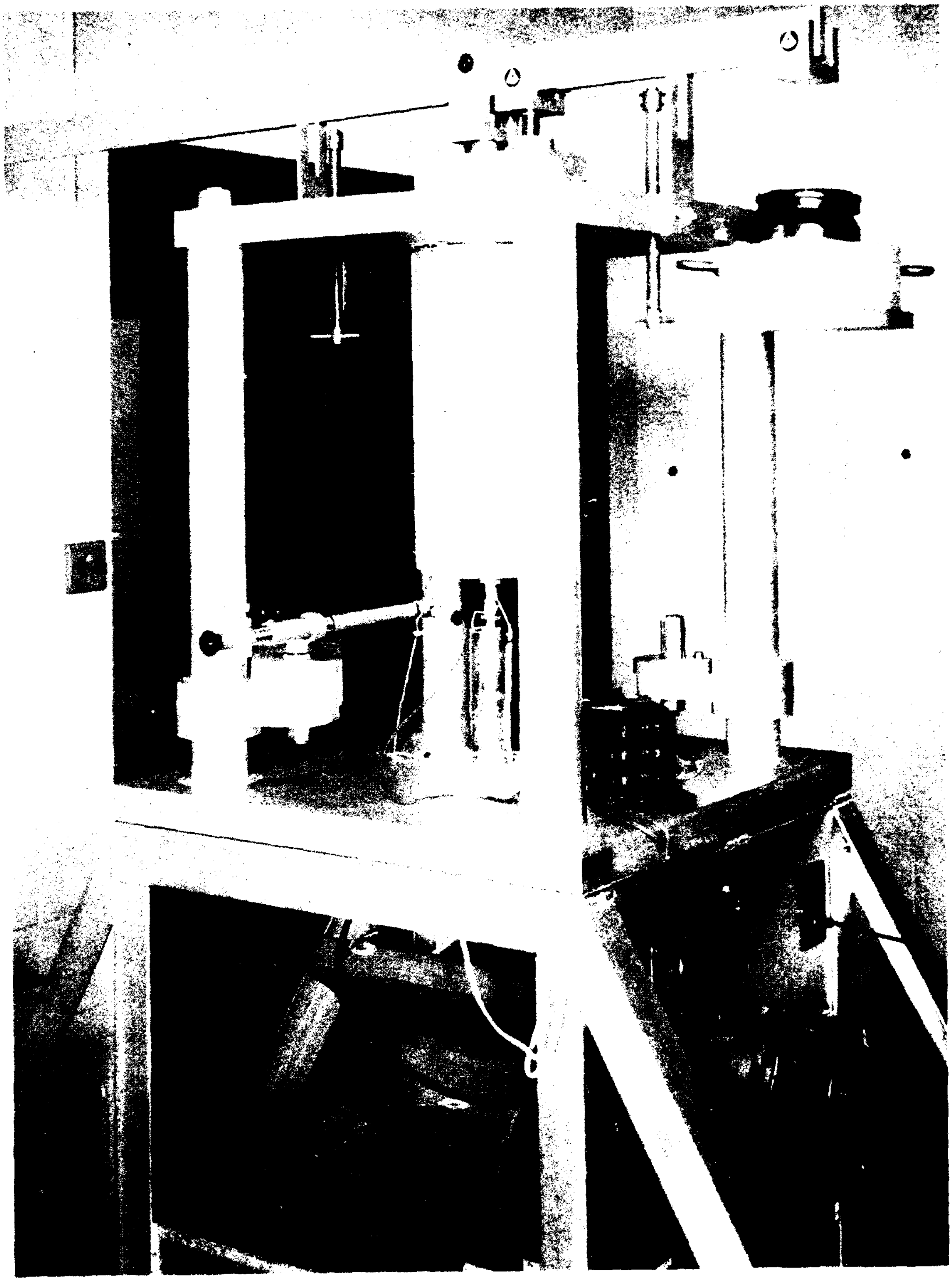


Parts

1 Welded base
2 Furnace
3 Support column
4 Top plate
5 Lever-arm stop
6 Control panel
7 Base plate
8 Bottom plate
9 Lower plunger
10 Microscope post support
11 Microscope post
12 Upper plunger pad
13 Upper plunger
14 Counterweight pan
15 Lever arm guide
16 Counterweight clevis
17 Knife edge
18 Lever arm
19 Leveling sleeve
20 Tension clevis
21 Compression clevis
22 Creep specimen
23 Lower plunger pad
24 Insulating collar
25 Loading clevis
26 Load pan

N20236

FIGURE 4. CREEP TESTING UNIT



N24349

FIGURE 5. COMPRESSION-CREEP TESTING UNIT WITH SPECIMEN AND MICROSCOPE IN PLACE

produced an average experimental lever-arm ratio of 16.05 ± 0.09 (a deviation of less than 1 per cent from the design value).

This creep unit was designed with the immediate aim of conducting compression-creep tests; however, it can be used for tension-creep tests as well. This can be accomplished simply by reversing the lever arm. The load capacity of this unit is sufficiently high to permit the creep testing of materials with strength characteristics well above those of the aluminum alloys.

The unit used for tension-creep testing was a dead-weight, lever-arm type like those shown in Figure 2 of WADC Technical Report 52-251, Part 1. This unit was equipped with an 18-inch-long closed tube furnace. The furnace was fitted with two windows so that creep measurements could be taken from each strip. This furnace had been adjusted in a series of exploratory tests until it yielded a maximum total variation in temperature of no more than $2^{o}F$ along the gage length.

PRESENTATION OF RESULTS ON ALUMINUM ALLOY 2024-T4

Static-Tension and Static-Compression Tests

Test Methods and Results

Material units of the aluminum alloy 2024-T4 were selected and machined into tension and compression specimens according to the techniques outlined earlier in this report.

Data from the room-temperature static-tension and static-compression tests are presented in Tables 1 and 2, and typical stress-strain curves are presented in Figures 6 and 7. These tests, and all subsequent static tests, were conducted at a strain rate of 0.0005 inch/inch/minute.

TABLE 1. STATIC-TENSION PROPERTIES OF 2024-T4 ALUMINUM ALLOY AT ROOM TEMPERATURE

Specimen Number	Modulus of Elasticity, 10^6 psi	Poisson's Ratio	Proportional Limit, psi	0.2% Offset Yield Stress, psi
282	11.4	0.281	36,000	45,800
185	11.0	0.324	36,500	45,200
158	10.8	-	37,000	45,400

TABLE 2. STATIC-COMPRESSION PROPERTIES OF 2024-T4 ALUMINUM ALLOY AT ROOM TEMPERATURE

Specimen Number	Modulus of Elasticity, 10^6 psi	Poisson's Ratio	Proportional Limit, psi	0.2% Offset Yield Stress, psi
101	11.6	0.334	32,500	42,200
20	11.5	-	33,500	42,200
5	11.6	0.330	32,500	41,700

Specimen No. 185

Proportional limit stress = 36,500 psi

0.2 % offset yield stress = 45,200 psi

Modulus of elasticity = 11.0×10^6 psi

Poisson's ratio = 0.324

Strain rate = 0.0005 in./in./min

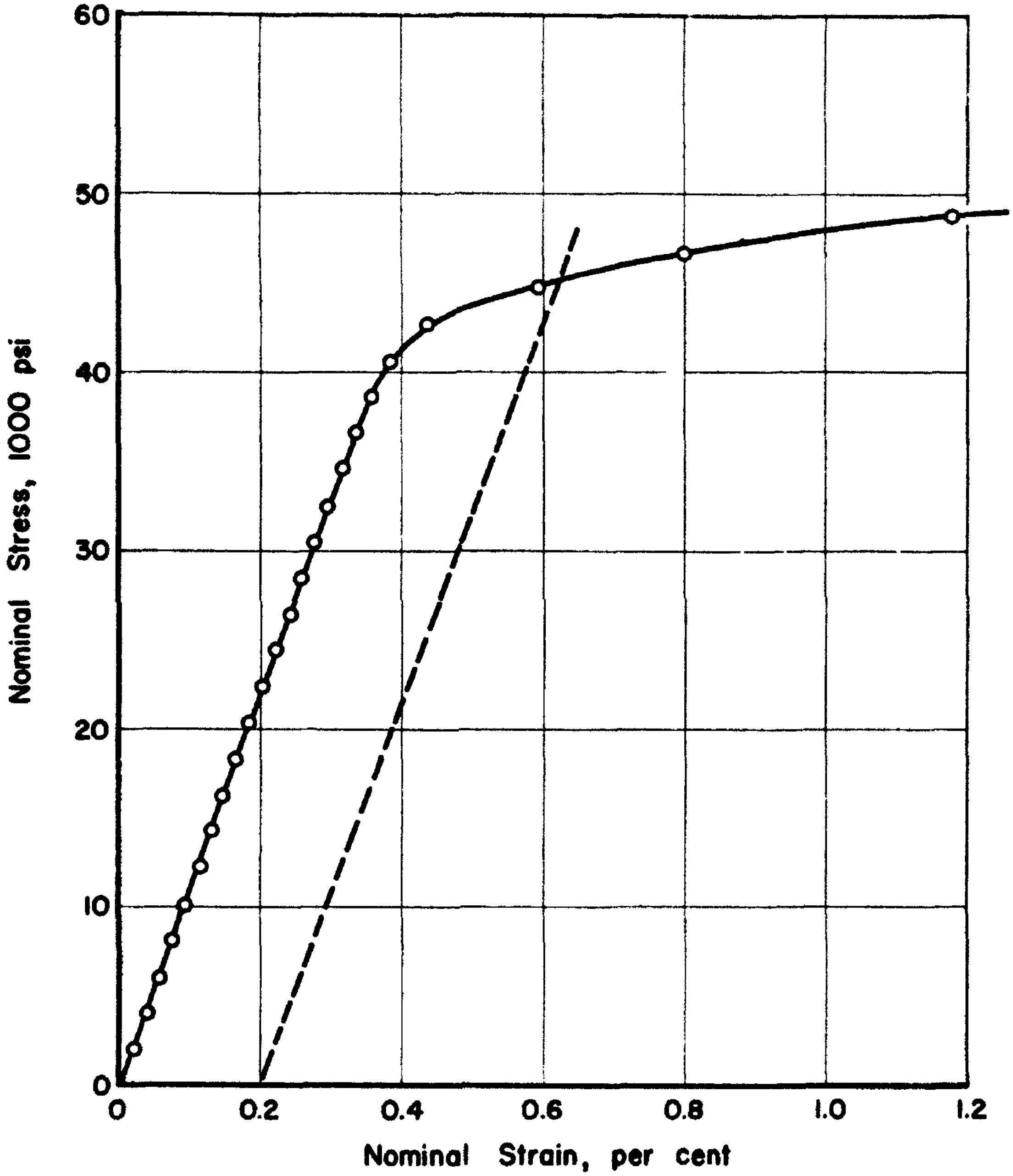


FIGURE 6. TYPICAL STATIC-TENSION STRESS-STRAIN CURVE FOR 2024-T4 ALUMINUM ALLOY AT ROOM TEMPERATURE

0-22836

Specimen No. 101
Proportional limit stress = 32,500 psi
0.2% offset yield stress = 42,200 psi
Modulus of elasticity = 11.6×10^6 psi
Poisson's ratio = 0.334
Strain rate = 0.0005 in./in./min

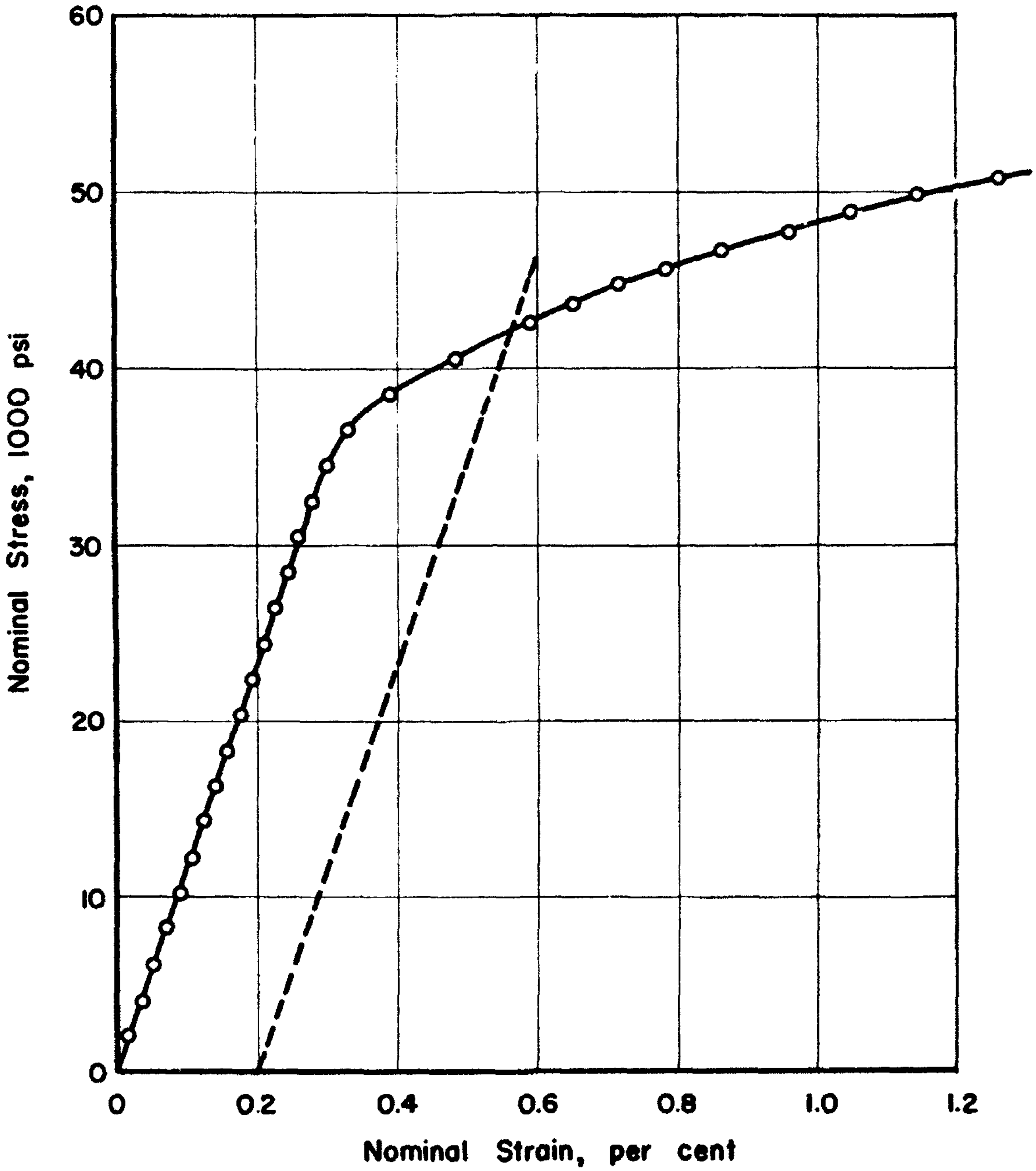


FIGURE 7. TYPICAL STATIC-COMPRESSION STRESS-STRAIN CURVE FOR 2024-T4 ALUMINUM ALLOY AT ROOM TEMPERATURE

0-22837

Standard SR-4-type strain gages were used to measure strains. Three gages, placed at intervals of 120 degrees, were used. A discussion of these results will be included in a subsequent section of this report.

One of the elevated test temperatures selected was 300°F. Preliminary tests indicated that for temperatures below 300°F, creep was insignificant. Strain readings were obtained by the use of Bakelite Type AB-3 strain gages. Three of these gages were cemented to each test specimen at intervals of 120 degrees. These gages were cured by the use of the schedule indicated below:

3 hours at 175°F (1 hour per gage)*

3 hours at 250°F (1 hour per gage)*

2 hours at 350°F

Dummy gages were prepared by fixing AB-3 gages to blocks of 2024-T4 aluminum alloy. During tests, the dummy gages were fastened near the test specimen to provide temperature compensation.

Tensile tests were conducted in the wire-wound furnace described earlier in this report.

The results of three tests conducted at 300°F on specimens subjected to the gage curing treatment described above are summarized in Table 3. In Figure 8, a comparison is made of the data obtained at room temperature and these data obtained at 300°F (aged 2 hours at 350°F). It is apparent that the curing treatment resulted in appreciable age hardening, since the curve at 300°F is above that for room temperature.

To establish this more definitely, three additional tests were conducted at 300°F. These tests were performed in exactly the same manner as the previous tests with the exception of the application of the Bakelite strain gages. In this second set of tests, all three gages were applied at

* The gages were cured under pressure to assure proper bonding.

TABLE 3. STATIC-TENSION PROPERTIES OF AS-RECEIVED 2024-T4 ALUMINUM ALLOY AT 300°F

(Subject to Curing Treatment at 350°F)

Specimen Number	Modulus of Elasticity, 10^6 psi	Poisson's Ratio	Proportional Limit, psi	0.2% Offset Yield Stress, psi
218	9.72	-	40,500	50,600
116	9.84	0.352	39,000	52,600
83	9.79	-	41,000	52,800

TABLE 4. STATIC-TENSION PROPERTIES OF AS-RECEIVED 2024-T4 ALUMINUM ALLOY AT 300°F

Specimen Number	Modulus of Elasticity, 10^6 psi	Proportional Limit, psi	0.2% Offset Yield Stress, psi
197	9.93	31,500	40,800
332	9.83	33,000	41,300
105	9.91	32,400	41,600

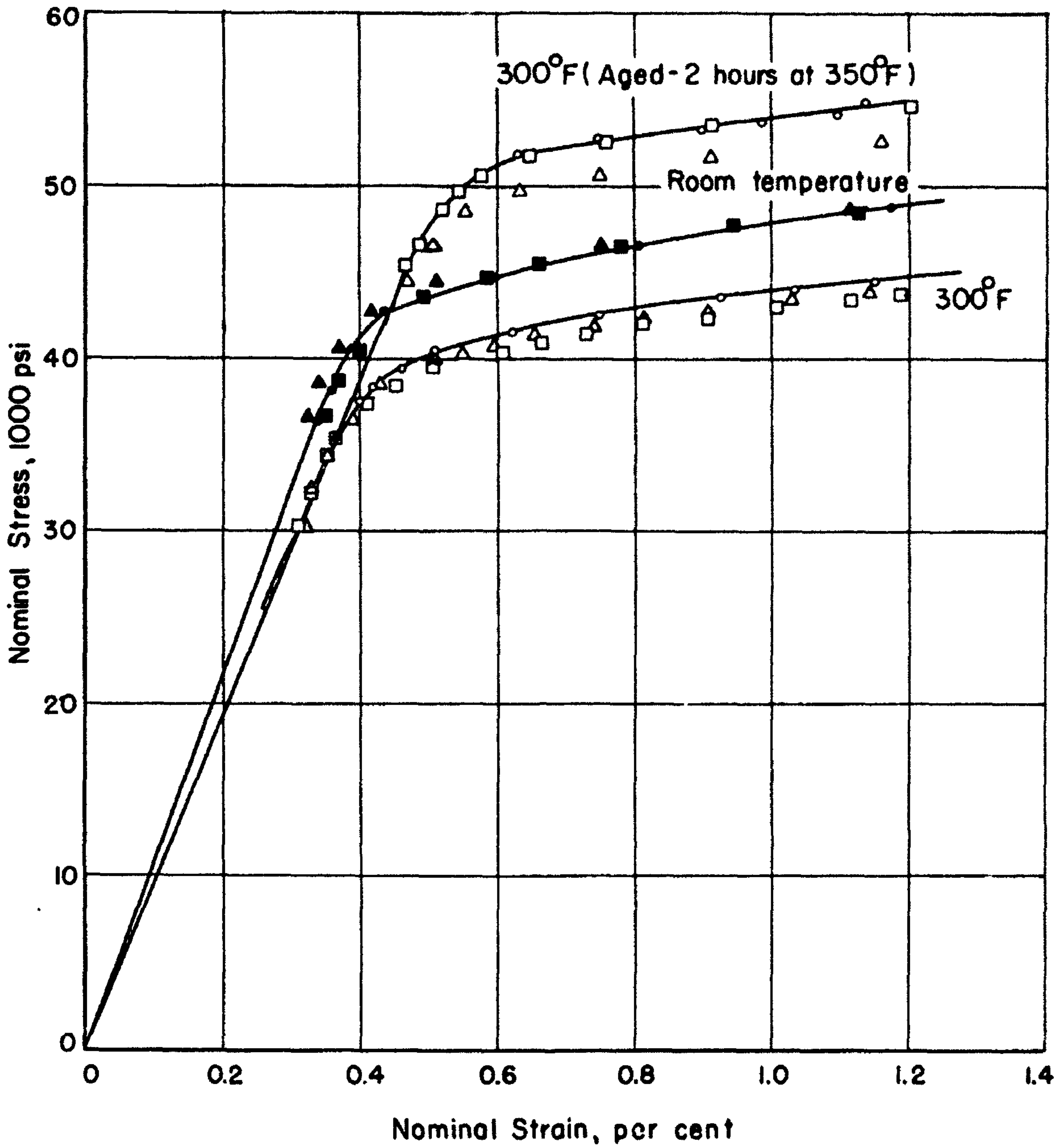


FIGURE 8. STATIC-TENSION STRESS-STRAIN CURVES FOR 2024-T4 ALUMINUM ALLOY

0-22940

once and subjected to the modified curing treatment outlined below:

1 hour at 175°F

1 hour at 250°F

1 hour at 300°F (prior to testing in the furnace)

Table 4 summarizes the results of these additional tests. For comparison, these results have also been plotted in Figure 8. The comparison of the results presented in Figure 8 suggests that the modified gage curing treatment did not introduce significant age hardening. That is, the general level of the repeated tests at 300°F was below that at room temperature.

Static-compression tests were also conducted at a test temperature of 300°F. For these tests, the modified gage curing treatment was used, and, as in all static tests, a strain rate of 0.0005 inch/inch/minute was maintained.

To obtain the test temperature, the compression subpress was placed in the Hevi Duty electric oven described previously in this report. In this oven, the maximum total temperature variation over the specimen length (5 inches) was 3°F. The results of these tests are summarized in Table 5. A discussion of these results will be presented in the next section of the report.

The final test temperature selected for a study of the aluminum alloy 2024-T4 was 375°F. For this alloy, age hardening at this temperature is very rapid as can be seen in Figure 9. A difference of a few minutes of exposure at 375°F can result in significant differences in hardness. The marked metallurgical instability at this temperature imposed considerable experimental difficulty in the performance of tests. Adjustments prior to testing must be kept at a minimum in order to reproduce test conditions - that is, exposure time at temperature. It should be noted that under such

TABLE 5. STATIC-COMPRESSION PROPERTIES OF AS-RECEIVED 2024-T4 ALUMINUM ALLOY AT 300°F

Specimen Number	Modulus of Elasticity, 10^6 psi	Proportional Limit, psi	0.2% Offset Yield Stress, psi
160	10.0	29,500	38,500
108	10.3	30,200	40,800
13	10.4	31,300	40,700

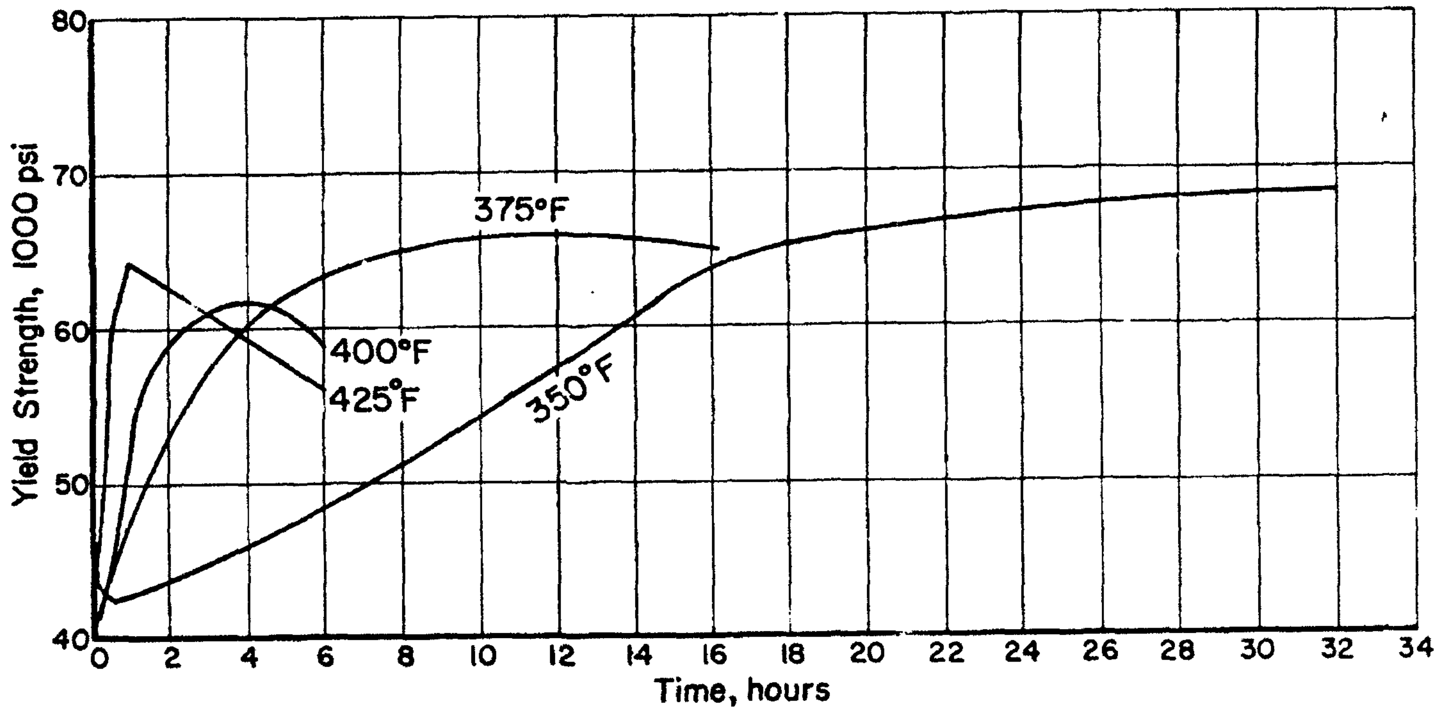


FIGURE 9. ARTIFICIAL AGING CURVES FOR 2024-T4 FLAT SHEET (AFTER DIX (12))

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circumstances, the selection of a preheating time depends primarily on the equipment being used.

To eliminate these difficulties, it was decided to stabilize the specimens to be tested at 375°F. This was done by preheating the specimens at 385°F for 258 hours prior to testing. Hardness surveys taken for times up to 432 hours indicated that a stable condition had been achieved by this treatment. These surveys were made on slugs cut from the ends of the material units in making the specimens. The slugs were from the same material units as the stabilized specimens. The average hardness increased from the as-received value of 75.7 Rockwell "B" to a peak and fell back to the as-received value within 24 hours. The hardness then continued to drop until it levelled off at a value of 72.5 Rockwell "B" after approximately 250 hours. Hence, there was a decrease in hardness between the as-received and the stabilized alloy. It should be emphasized that the stabilization treatment used applies to an unstressed state only. It is possible that additional changes due to strain-induced precipitation may have occurred in subsequent testing. This would probably be more likely to occur during creep tests than during static tests.

Two points should be noted with regard to the treatment. A simplification and improved control of test procedure was achieved. No drastic loss in strength was encountered (this would occur, of course, if this alloy were overaged).

The test equipment and procedures used for the tests conducted at 375°F were identical to those used in the preceeding static tests. One point should be noted, however. Creep at high stress levels - of the order of the 0.2 per cent offset yield strength - at 375°F was very marked. As a consequence, the strain rate of 0.0005 inch/inch/minute was not sufficiently rapid to prevent appreciable creep from taking place. It should be recognized, therefore, that this alloy was, in this sense, quite sensitive to strain rate during the latter part of the stress-strain curves. A faster rate would have decreased the time-dependent component of flow, and would, of course, have resulted in a "raising" of the stress-strain curves.

The results of tension and compression tests at 375°F are presented in Figure 10 and in Tables 6 and 7. A discussion of these results is included in the next section of this report.

Table 8 summarizes the static data obtained on the 2024-T4 aluminum alloy.

Discussion of Results

In discussing the static-tension and compression results, emphasis will be placed on two comparisons. One will be a comparison of these data with one another. A second area of discussion will involve a comparison of the data obtained in this study with that obtained in another study[3].

Before beginning the discussion involving the first comparison, it might be well to review some of the information available on fabrication history in terms of its relation to tensile and compressive properties.

In 1881, Bauschinger[13] discovered that a plastically deformed specimen exhibited an increased resistance to flow upon reloading in the same direction, but a reduced resistance to flow upon reloading in the opposite direction. Since that time, the so-called Bauschinger effect has been used to explain behavior observed subsequent to various states of prestrain. Lynch, Ripling, and Sachs[14], for example, observed a "Bauschinger effect" in tensile-test specimens that had been subjected to prior compression, extrusion, or drawing.

An interpretation of this type immediately suggests the possibility that the relation of prestrain or fabrication history to the subsequent tensile and compressive behavior of metals may be readily understood. In a

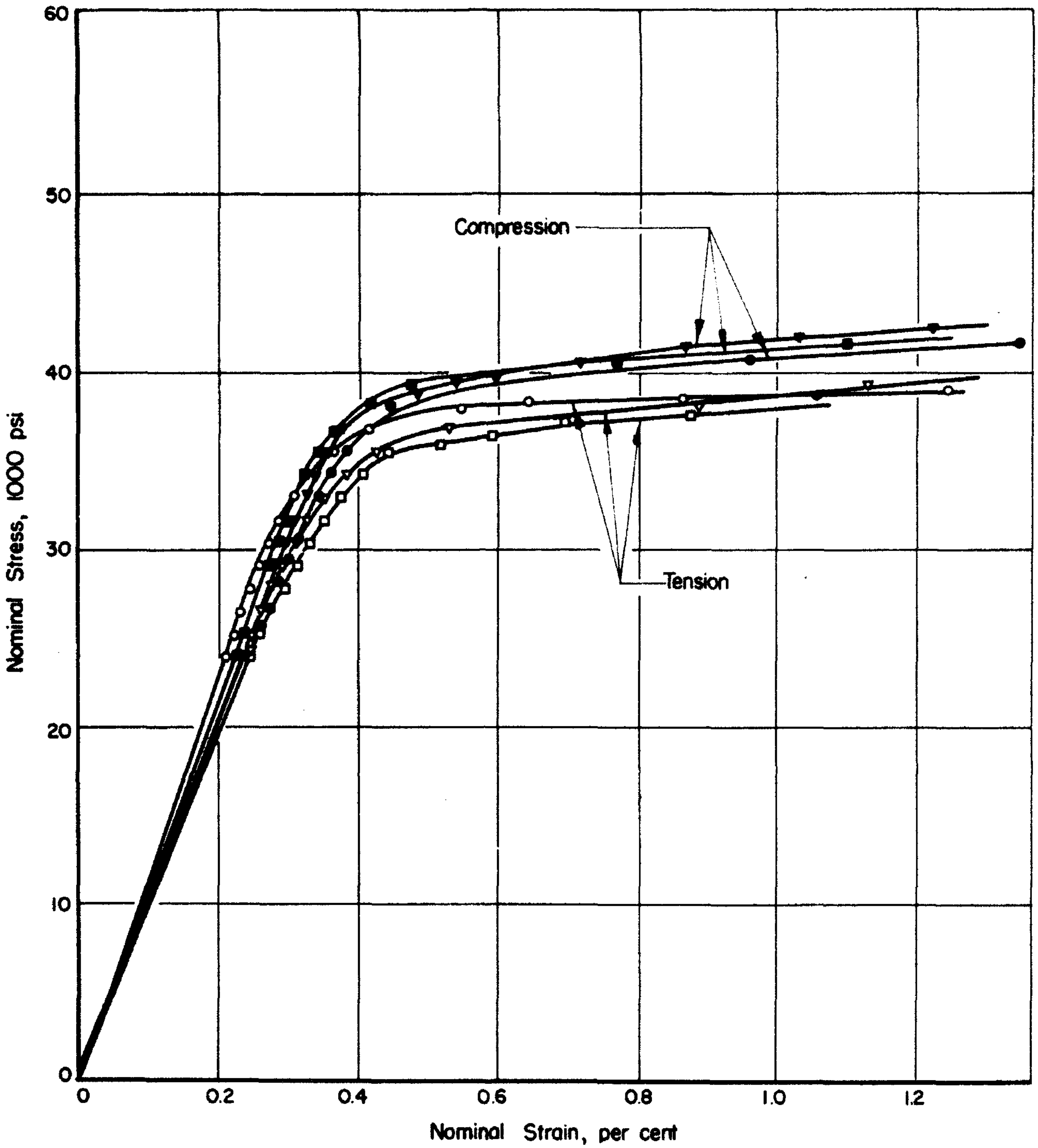

FIGURE 10. STATIC TENSION AND COMPRESSION STRESS-STRAIN CURVES FOR 2024-T4 ALUMINUM ALLOY AT 375°F

TABLE 6. STATIC-TENSION PROPERTIES OF AS-RECEIVED* 2024-T4 ALUMINUM ALLOY AT 375°F

Specimen Number	Modulus of Elasticity, 10^6 psi	Proportional Limit, psi	0.2% Offset Yield Stress, psi
304	11.5	23,800	37,800
142	10.0	23,400	36,400
337	10.5	26,000	36,800

* Heated at 385°F for 258 hours.

TABLE 7. STATIC-COMPRESSION PROPERTIES OF AS-RECEIVED* 2024-T4 ALUMINUM ALLOY AT 375°F

Specimen Number	Modulus of Elasticity, 10^6 psi	Proportional Limit, psi	0.2% Offset Yield Stress, psi
188	10.7	30,500	40,100
249	10.4	33,000	39,800
189	9.92	31,000	39,600

* Heated at 385°F for 258 hours.

TABLE 8. MEAN STATIC PROPERTIES OF 2024-T4 ALUMINUM ALLOY

Stress State	Temperature, °F	Modulus of Elasticity, 10^6 psi	Proportional Limit Stress, psi	0.2% Offset Yield Stress, psi
Tension	80	11.1	36,500	45,500
	300	9.9	32,300	41,200
	375	10.7	26,600	37,000
Compression	80	11.6	32,800	42,000
	300	10.2	30,300	40,100
	375	10.3	31,500	39,800

comment on the above paper, however, Bridgeman[15] cautions against an attempt at too simple a generalization along these lines. Correlations observed by Lynch et al. were obtained only for small amounts of prestrain. Bridgeman indicates that he had observed that, for large amounts of prestrain in compression, hardening occurred for subsequent tension in all directions. As a consequence, there is, after a drop in the resistance to flow after small prestrains, an increase in resistance to flow after intermediate and large prestrains.

In addition to the above complications, commercial alloys are often subject to the effects of still another factor. Their history frequently includes heat treatments subsequent to working processes. Studies by Ancker, Parker, and Hazlett[16] on nickel alloys have shown that the effects of prestrain are retained after annealing at moderate temperatures. He was also able to show a correlation between the retained effects of prestrain in terms of flow stress and the size of substructure. Although these results were for tension only, it is reasonable to assume that differences between tensile and compressive behavior may also be altered by the annealing temperature.

Returning now to the data on the aluminum alloy 2024-T4, it was observed that, at room temperature and at 300°F, the resistance to flow was greater, initially at least, in tension than in compression. Although this may be attributed to the introduction of a Bauschinger effect during the rolling of the bar stock from which the specimens were machined, the work of Bridgeman suggests that this should be considered, at best, a tentative explanation. Before this can be resolved, the effects of prestrain in rolling should be carefully studied.

At a test temperature of 375°F, the resistance to flow in compression was superior to that in tension. Although this may possibly be related to a difference in the aging treatment that these specimens received, it is felt that the change in behavior from that observed above was related to the creep resistance of the material. In creep tests, the resistance to creep at this temperature was significantly less in tension than in compression. Also, the general resistance to creep was lower at 375°F than at 300°F. For these reasons, it is suspected that the time-dependent component of flow in the so-called "static" curves for 375°F was quite significant, and that it caused merely an apparent reversal in the static resistance to flow. A tension test and a compression test at room temperature of 2024-T4 specimens which had been stabilized would help to establish whether creep was the source of this reversal.

The above discussion has highlighted the influence of history. It is, therefore, of interest to compare the above results with those available for the same alloy that has had a different history. The comparisons made will be confined to room-temperature results since this was the only common temperature in the two studies.

The predominant difference between the results of the two studies was that the resistance to flow was significantly higher for the material used in the previous study.

A search of the literature indicated that Dorn, Pietrokowsky, and Tietz[17] had observed that the resistance to plastic deformation of pure aluminum was markedly affected by grain size. Zener[18], in establishing a theoretical criterion for the initiation of slip bands, derived an expression that indicated that the flow stress is inversely proportional to the square root of the grain diameter.

Inasmuch as the bar stocks from which the aforementioned specimens were machined were of different diameter (5/8 inch for the previous study and 1-1/4 inches for the present), it was felt that the grain size might be different. Grain-size measurements were obtained by counting the grains intersecting a line across a transverse section of the bar stock. A total of four counts was made, and the specimen was rotated to obtain counts along different directions. The average grain size for the 5/8-inch bar stock was 0.0021 inch (ASTM grain-size Numbers 5 and 6), and for the 1-1/4 inch it was 0.0043 inch (ASTM grain-size Numbers 3 and 4). It is interesting to note that this grain-size difference also was evident in the longitudinal direction. In both of the bar stocks, the grains appeared elongated in the direction of previous working, as compared to their equiaxed structure in the transverse sections.

If D_s* is designated as the grain diameter for the 5/8-inch bar stock, and D_L for the 1-1/4-inch bar stock, the ratio

$$\left(\frac{D_L}{D_s}\right)^{1/2} = \left(\frac{0.0043}{0.0021}\right)^{1/2} = 1.4 \quad .$$

According to Zener

$$\left(\frac{D_L}{D_s}\right)^{1/2} = \frac{\sigma_s}{\sigma_L} \quad ,$$

where σ_s and σ_L are the yield stresses for the small- and large-grained specimens, respectively. The average values of yield strength obtained for the two materials are given in the tabulation below.

Type of Test	Stock Diameter, inch	0.2% Offset Yield Stress, psi	$\frac{\sigma_s}{\sigma_L}$
Tension	5/8	55,100	1.2
Tension	1-1/4	45,500	1.2
Compression	5/8	59,100	1.4
Compression	1-1/4	42,000	1.4

The ratio of the stress values obtained tends to confirm the approximate validity of the Zener relation as applied to this alloy.

* The grain diameter referred to is that observed in the transverse sections. For axial loading, slip within grains would be expected to be limited or controlled more by this dimension than by the longitudinal diameter.

It would appear that the marked difference in the resistance to plastic flow of these two bar stock sizes can be attributed largely to the difference in grain size. In general, grain boundaries exert a strengthening effect in metals by restraining low-temperature plastic flow. Inasmuch as adjacent grains have different crystallographic orientations, boundary atoms do not fit both lattices and slip planes do not match. At the grain boundaries, slip becomes discontinuous, introducing local lattice disturbances. As the grain size decreases, the total number of grain boundaries increases. Accordingly, the hindering effect to plastic flow increases. A fine-grained material, therefore, would be stronger than a coarse-grained material. This, of course, has been noted in many studies.

It should be noted that a secondary effect appears to be present from the above tabulation. The resistance to plastic flow in compression was greater than in tension for the 5/8-inch bar stock material. For the 1-1/4-inch bar stock, however, this behavior was reversed. Until the effect of the degree of rolling reduction is more clearly understood, however, it does not seem likely that this behavior can be explained.

Tension- and Compression-Creep Tests

Tension- and compression-creep tests were performed on 2024-T4 aluminum alloy creep specimens at the same elevated temperatures as used in the static tests, 300°F and 375°F. Tension-creep and compression-creep tests were conducted on specimens of the design shown in Figure 1-c. Platinum-strip extensometers were fastened to each specimen in the manner shown in Figure 2.

The tension-creep tests on the 2024-T4 specimens were conducted in a dead-weight, lever-arm type test frame like those shown in Figure 2 of WADC Technical Report 52-251, Part 1. Each specimen was placed in the stand and the closed-tube furnace positioned. A small load was then applied to check the operation of the strips (approximately 1500 psi) and the specimen heated to temperature. In the case of the tests at 300°F, the specimen was heated to temperature in one hour and allowed to remain at 300°F for one hour before final loading. This preheating time was the same used in the static tests at 300°F.

Measurements of creep deformation were made by measuring the relative movements of reference marks on each strip. Measurements were taken from each of two strips mounted on opposite sides of the creep specimens.

It is important to point out that, since measurements of deformation of the order of 10 microinches were desired in these tests, it was necessary to know the temperature (and particularly the variation in temperature) of the specimen at the time of every measurement. The importance of this precaution becomes apparent when it is realized that a change in temperature of only one degree would bring about thermal expansions or contractions which would cause a movement of 20 microinches between reference marks. Hence, if uncorrected, temperature variations during a creep test could introduce "apparent deformations" which could conceivably overshadow creep deformations of the order desired in this program. In an attempt to eliminate these "apparent deformations", the temperature of the specimen was recorded from three thermocouples on the specimen along with each reading of a strip (or every 3 to 4 minutes while reading a strip).

The "reading" of a strip consisted of aligning the filar micrometer cross hairs with the tip of a reference mark on either the male or female part of the strip, recording the initial reading of the filar micrometer drum, then aligning the cross hairs with an adjacent mark on the other part of the strip, and recording the final reading of the filar micrometer drum. This process of "reading" a strip involved the ability of the human eye to distinguish the coincidence of a very fine line and the tip of a small mark.

In order to reduce human errors, a relatively large number of readings (8 to 15) were taken from each strip at one time. The temperature of the specimen was recorded several times during the taking of a set of such readings. In order to determine the true distance, $\triangle$, between a pair of reference marks, it was first assumed most scatter in a set of initial and final readings of the micrometer drum arose from natural or random causes and, hence, that the scatter was random. Under these conditions, the "true" value would be the most probable value, or that value which appeared most frequently in a large set of readings. By arranging a set of initial and final drum readings in order of increasing value, it was possible to determine the most probable value, $\triangle$, for each strip. The value of $\triangle$ was then corrected for the difference between the desired test temperature and the mean specimen temperature at the time of reading. The two corrected values of $\triangle$ for each strip were then averaged to give the final value of creep strain.

In the case of the tension-creep tests at 375°F, it was not necessary to adhere closely to the practice of limiting the preheating time to 2 hours since the specimens tested at 375°F had been stabilized as described earlier.

Compression-creep testing of these two materials was carried out in the creep unit described previously and shown in Figure 5.

After the strip extensometers had been mounted on a specimen and the specimen placed in the machine, four thermocouples were attached to the specimen (see Figure 1). The control thermocouple was imbedded in the lower shoulder and the three others tied to the top, center, and bottom of the gage section. These thermocouples aided in the determination of the average temperature in the gage section. This average temperature was used as described in the tension-creep tests in an attempt to determine the effect upon instantaneous strip readings of the thermal expansion and contraction of the specimen and the strip extensometers.

To prepare for a compressicn-creep test, each specimen was aligned at room temperature by applying a load approximately equal to one-third of the proportional limit load, and rotating the upper plunger and plunger pad until equal deformations were observed on each strip. Exploratory tests conducted on specimens with SR-4-type strain gages connected to the gage section indicated alignment obtained in this manner was reproducible on subsequent unloading and reloading at higher stress levels. Furthermore, measurements made from specimens tested during this period indicated that alignment obtained in the above manner at room temperature was maintained at elevated temperatures.

Following the alignment of the specimen at room temperature, the specimen was unloaded and the furnace lowered. The specimen was then heated to the test temperature in the same manner as employed in the tension-creep and static testing of 2024-T4.

Immediately following the application of the test load, a series of readings was taken from each strip extensometer. Simultaneous readings were taken of the three thermocouples attached to the gage section of the specimen. Measurements indicated that the maximum temperature variation within the gage section on the specimen was of the order of 4 degrees. Compression-creep data obtained were prepared in the same manner as tension-creep data, with one exception. An examination of the compression-creep data suggested that specimens were not subject to completely free expansion. Hence, the correction applied to tension-creep data for small variations in specimen temperature could not be applied to compression-creep data. As a result, compression-creep data presented in this report were not corrected for the effect of thermal variations. In regard to the matter of temperature control in creep testing, it is important to point out that where measurements of relatively small creep deformations are necessary, the limitation of temperature cycling to less than 2 degrees (minimum to maximum) is highly desirable.

Tension- and compression-creep curves obtained on 2024-T4 aluminum alloy at 300°F and 375°F are given in Figures 11 through 16. In each figure, tension- and compression-creep data at the same temperature and stress level are presented together for comparison. These data indicate that, for the 2024-T4 alloy studied, significant differences existed between tensile- and compressive-creep data at all the stress levels at both temperatures. At each stress, considerably more creep took place in tension than in compression.

It should be noted that at 300°F the 12,000 and 30,000 psi creep curves exhibited a marked inflection point, that is, a levelling off, followed by an increase in creep rate. At 30,000 psi, this inflection point occurred in the region of 50 hours. At 12,000 psi, this inflection was quite marked. In fact, the increase in creep strain appears to have been halted over the region from 15 to 50 hours. The data obtained in some cases actually indicated a decrease in creep strain in the region; this latter behavior does not seem compatible with accepted concepts of creep behavior. Carlson[19] has reported observing a similar inflection point on a 2024-T4 alloy at 350°F and 450°F. In his tests, this phenomenon exhibited itself most visibly at stress levels of the order of 45,000 psi; however, he pointed out that the visibility of this inflection increased as the scale of the ordinate, creep strain, was increased. Finlay and Hibbard[20] attributed the existence of a similar phenomenon observed in a 4 per cent aluminum-copper alloy to precipitation phenomena. Figure 9, presented earlier in this report, would seem to indicate that aging at temperatures of the order of 350°F to 450°F would cause the yield strength to increase for a

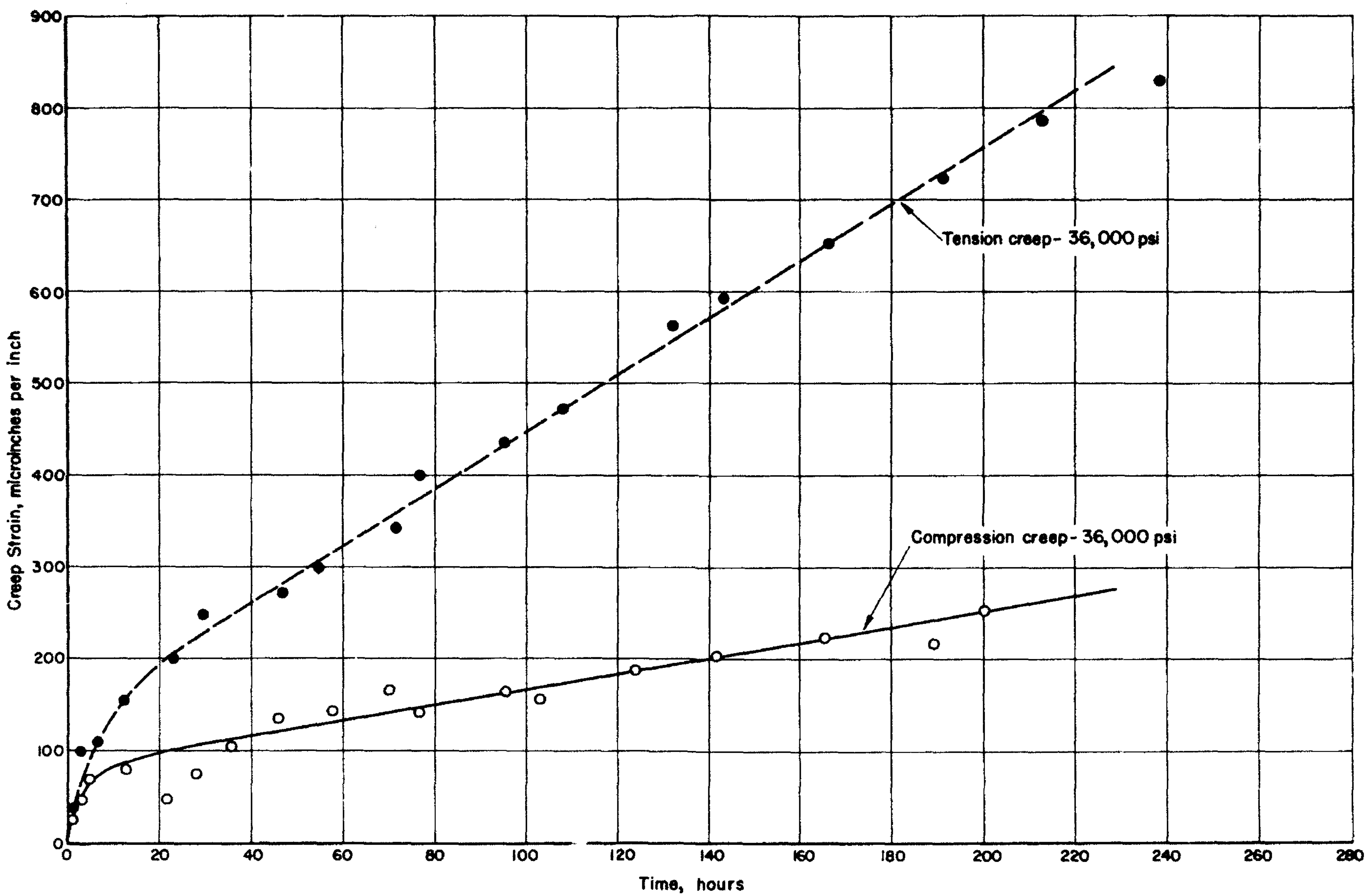

FIGURE 11. COMPARISON OF TENSION-AND COMPRESSION-CREEP CURVES FOR 2024-T4 ALUMINUM ALLOY TESTED AT 300°F

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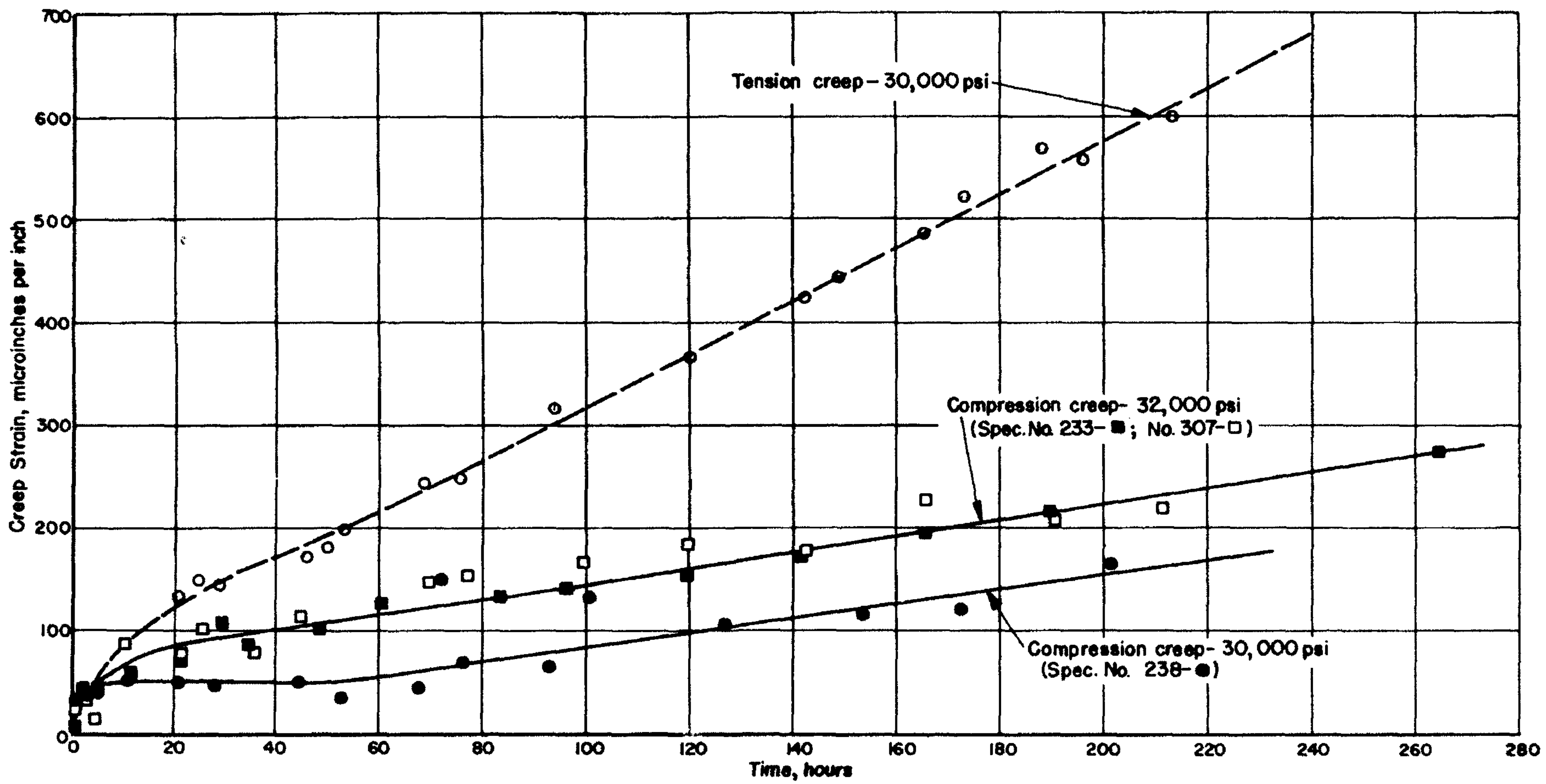

FIGURE 12. COMPARISON OF TENSION-AND COMPRESSION-CREEP CURVES FOR 2024-T4 ALUMINUM ALLOY TESTED AT 300°F

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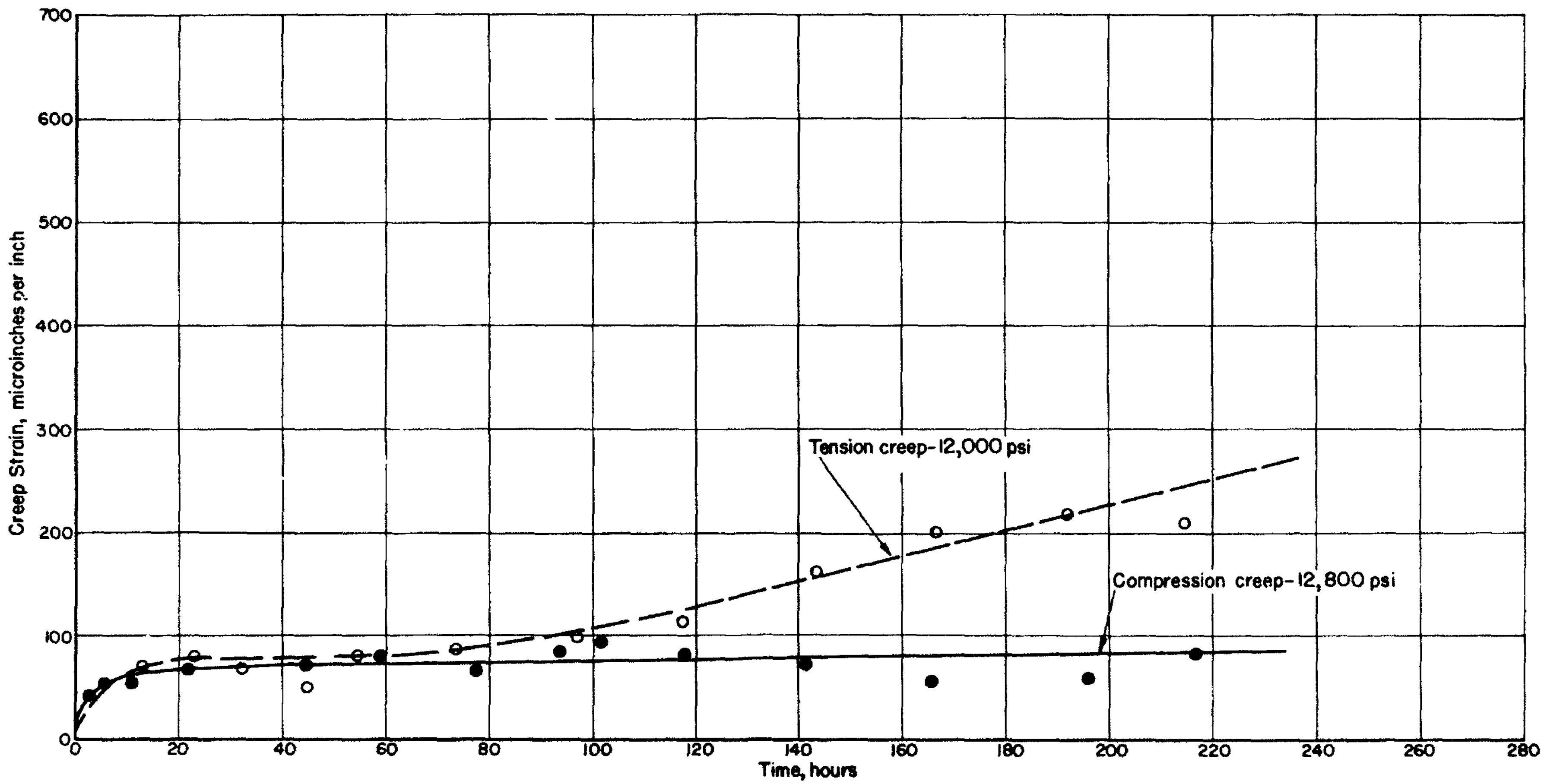

FIGURE 13. COMPARISON OF TENSION-AND COMPRESSION-CREEP CURVES FOR 2024-T4 ALUMINUM ALLOY TESTED AT 300°F

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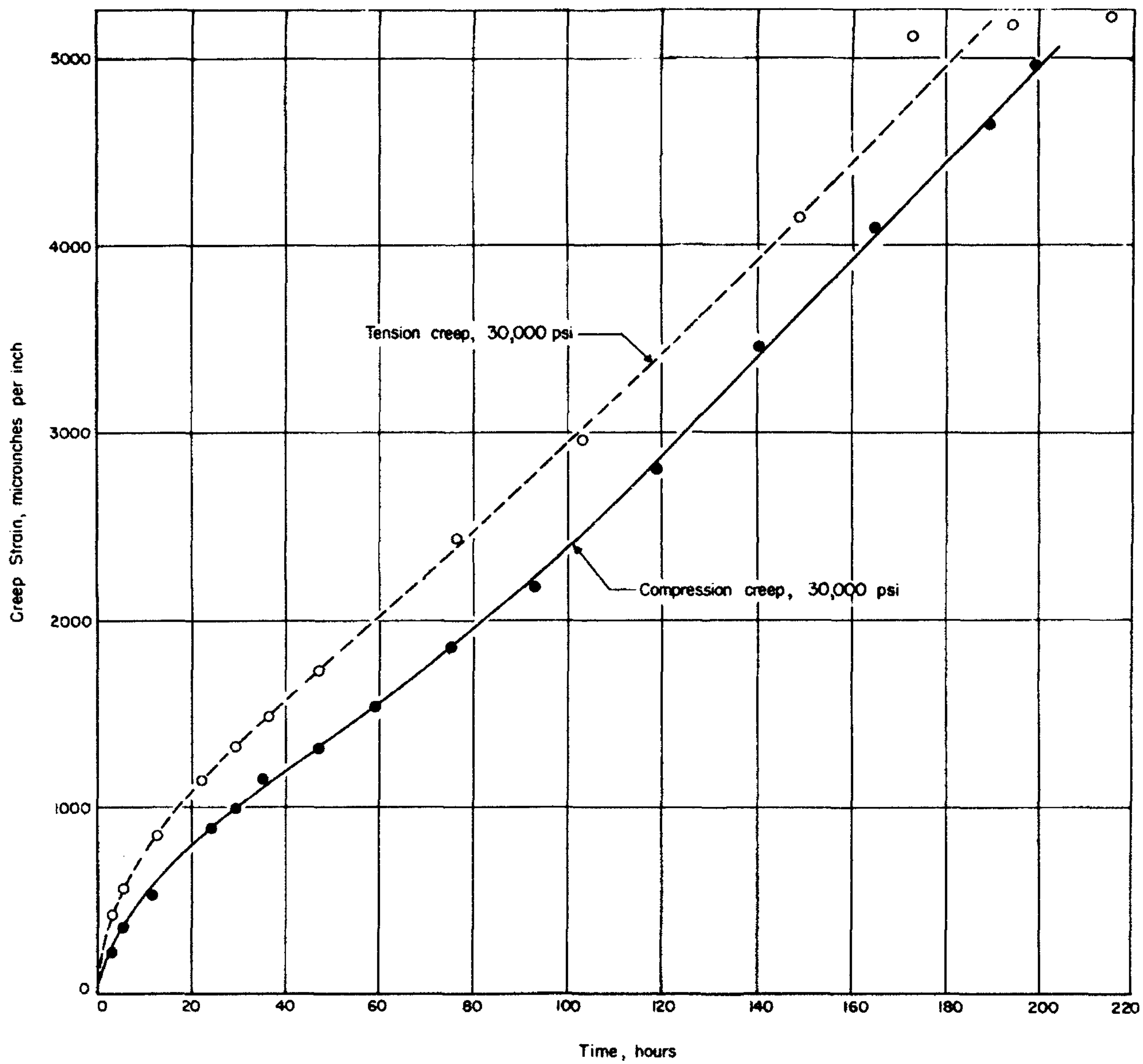

FIGURE 14. COMPARISON OF TENSION-AND COMPRESSION—CREEP CURVES FOR 2024—T4 ALUMINUM ALLOY AT 375° F

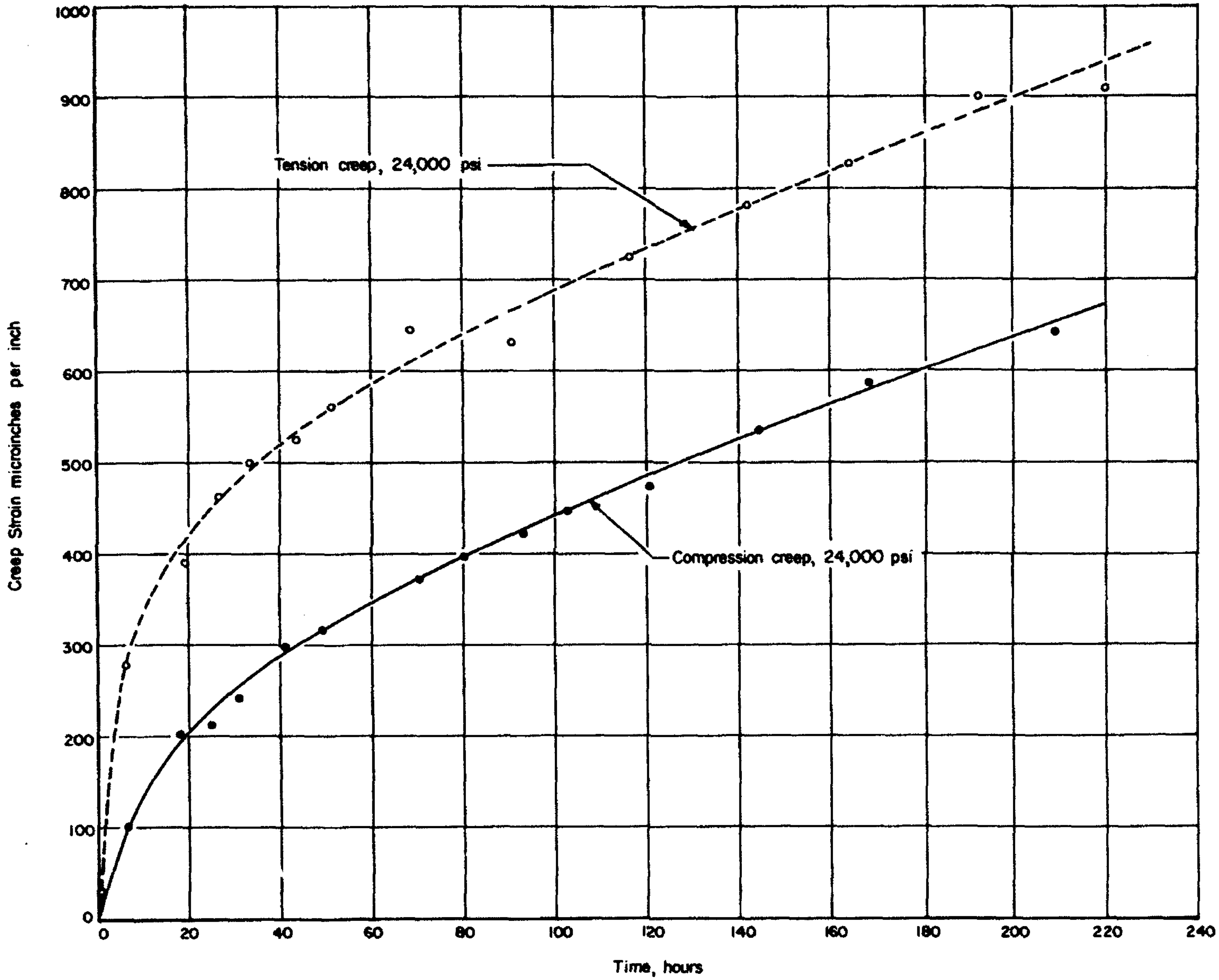

FIGURE 15. COMPARISON OF TENSION- AND COMPRESSION-CREEP CURVES FOR 2024-T4 ALUMINUM ALLOY AT 375°F

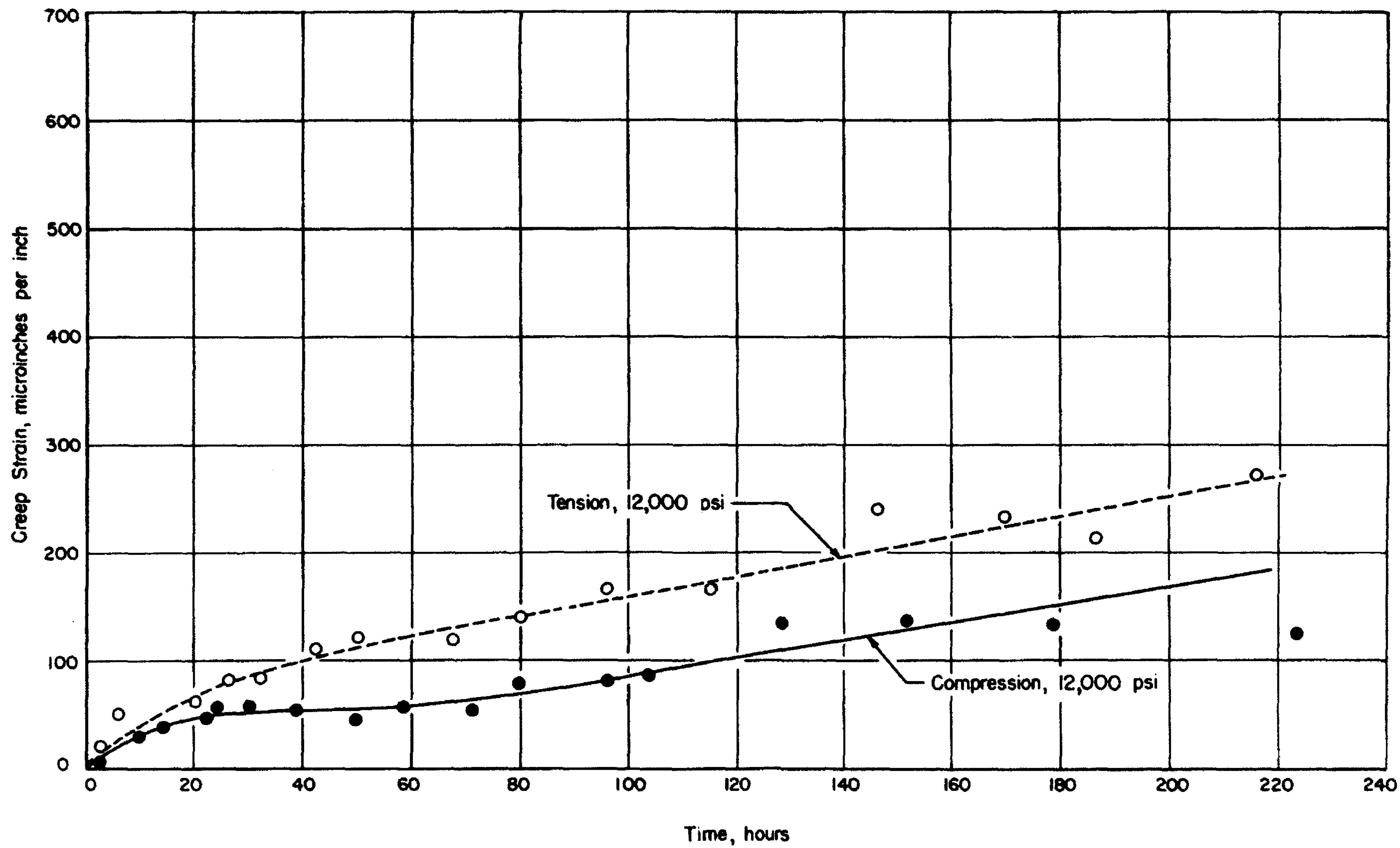

FIGURE 16. COMPARISON OF TENSION-AND COMPRESSION-CREEP CURVES FOR 2024-T4 ALUMINUM ALLOY AT 375° F

period of time, dependent on the temperature, and then to decrease. This behavior is also supported by observations of Barer[21] on a similar aluminum alloy. The curves in Figures 11, 12, and 13 would seem to indicate that the peak yield strength caused by aging at 300°F might be expected to appear some time after 20 hours. In this respect, the inflection phenomenon visible in these curves might be considered due to age hardening.

The creep curves in Figures 14, 15, and 16 on the 2024-T4 alloy at 375°F indicate a somewhat different behavior than the data at 300°F. At 375°F, as at 300°F, the total creep in tension was always greater than in compression. At 300°F, a marked difference was also observed in the 200-hour creep rates in tension and compression. This latter difference was not observed at 375°F. In fact, as Figures 15, 16, and 17 show, the creep rates were almost identical in tension and compression beyond 100 hours. What differences existed between tension and compression creep appear to have been introduced before a time of 80 hours. Such a behavior would suggest that these differences were due to differences in primary creep behavior. These data suggest the possibility that stabilization at 375°F may have removed the cause of differences in secondary tension and compression creep. It is also possible that this behavior is a temperature effect.

It was pointed out in the introduction to this report that certain investigators[4] have observed that wrought metals exhibited greater creep resistance in tension than compression. The creep data obtained in this investigation are not in agreement with this conclusion. These data lend support to the proposal made in the introduction that differences in compression- and tension-creep resistance may be due to the previous history of the material.

The work of Carlson and Manning[3] on the same 2024-T4 alloy (of a different lot) has been referred to previously. These investigators studied the creep of this alloy at 350°F and 450°F, in stabilized and as-received conditions. They stabilized their alloy at 600°F for 100 hours. Although their primary interest was not that of studying the differences between tension and compression creep, their data indicated that the creep resistance of the stabilized alloy was greater in tension than compression at 450°F.

For the as-received alloy, they found a greater creep resistance in tension than compression at 450°F, but at 350°F, they found the reverse - greater creep resistance in compression than tension. Table 9 gives a comparison of the two sets of data on 2024-T4 aluminum.

The comparisons in Table 9 suggest that there is a reversal in the nature of the creep resistance somewhere between 375°F and 450°F. At 300°F, the difference in tension and compression creep was quite marked both in the primary and secondary stages (see Figures 11, 12, and 13). The data of Carlson and Manning at 350°F indicate that greater creep still takes place in tension, but that these differences arise almost wholly in the primary stage. The data of this study at 375°F show substantially the same type behavior even though the specimens had been stabilized. At 450°F, both stabilized and unstabilized materials exhibited more creep in compression. In the case of the stabilized material tested at 450°F, the differences in creep behavior appear to have been confined again to the primary stage. The implication of the comparison is that the differences between tension- and compression-creep strain in 2024-T4 aluminum alloy may be primarily a reflection of temperature. The results in Table 9 would seem to indicate that stabilization has not altered this behavior, and, in fact, that differences in grain size may have only a secondary effect. It is probable that the mode of creep deformation of this alloy may change as the temperature is raised. However, before such a behavior can be considered further, additional creep data should be

TABLE 9. COMPARISON OF CREEP RESISTANCE OF 2024-T4 ALUMINUM ALLOYS

(T - Tension, C - Compression)

Condition	Stabilized				As-Received			
Temperature, °F	300	350	375	450	300	350	375	450
This Investigation			C > T		C > T			
Carlson and Manning[19]				T > C		C > T		T > C

obtained on this alloy. It is hoped that some additional work will clarify some of these points.

PRESENTATION OF RESULTS ON 1100-0 ALUMINUM

Static-Tension and Static-Compression Tests

Material units of aluminum 1100-0 were selected for tension and compression specimens according to the procedures outlined earlier in this report. Bar stock was obtained in the 1100-F (approximately 1/2 hard) condition to facilitate machining. Following machining, the specimens were annealed at 650°F for 1 hour. This treatment reduced the hardness from approximately Rockwell "H" 71 to about Rockwell "H" 40.

Metallographically, the microstructure was normal in appearance. In a transverse section, the annealed material had an equiaxed structure with an ASTM grain-size rating of Numbers 3 and 4. Longitudinally, the grains were elongated in the direction of rolling. It should be noted, however, that the grain elongation was less marked in the 1100-0 condition than in the 1100-F condition.

Tests were conducted at room temperature and at 300°F. Test equipment and test procedures were the same as those used in static tests on the aluminum alloy 2024-T4. As previously, the strain rate for all tests was 0.0005 inch/inch/minute.

Results for room temperature are summarized in Tables 10 and 11, and presented graphically in Figure 17. The results for a test temperature of 300°F are summarized in Tables 12 and 13, and presented graphically in Figure 18.

As can be seen from these data, the difference between these tension and compression data appears to be insignificant. The differences that do

TABLE 10. STATIC-TENSION PROPERTIES OF 1100-0 ALUMINUM AT ROOM TEMPERATURE

Specimen Number	Modulus of Elasticity, 10^6 psi	Poisson's Ratio	Proportional Limit, psi	0.2% Offset Yield Stress, psi
339A	9.91	-	1750	4300
329A	9.63	0.34	2175	4370

TABLE 11. STATIC-COMPRESSION PROPERTIES OF 1100-0 ALUMINUM AT ROOM TEMPERATURE

Specimen Number	Modulus of Elasticity, 10^6 psi	Poisson's Ratio	Proportional Limit, psi	0.2% Offset Yield Stress, psi
99A	11.3	-	1600	4300
48A	10.5	0.42	2100	4500

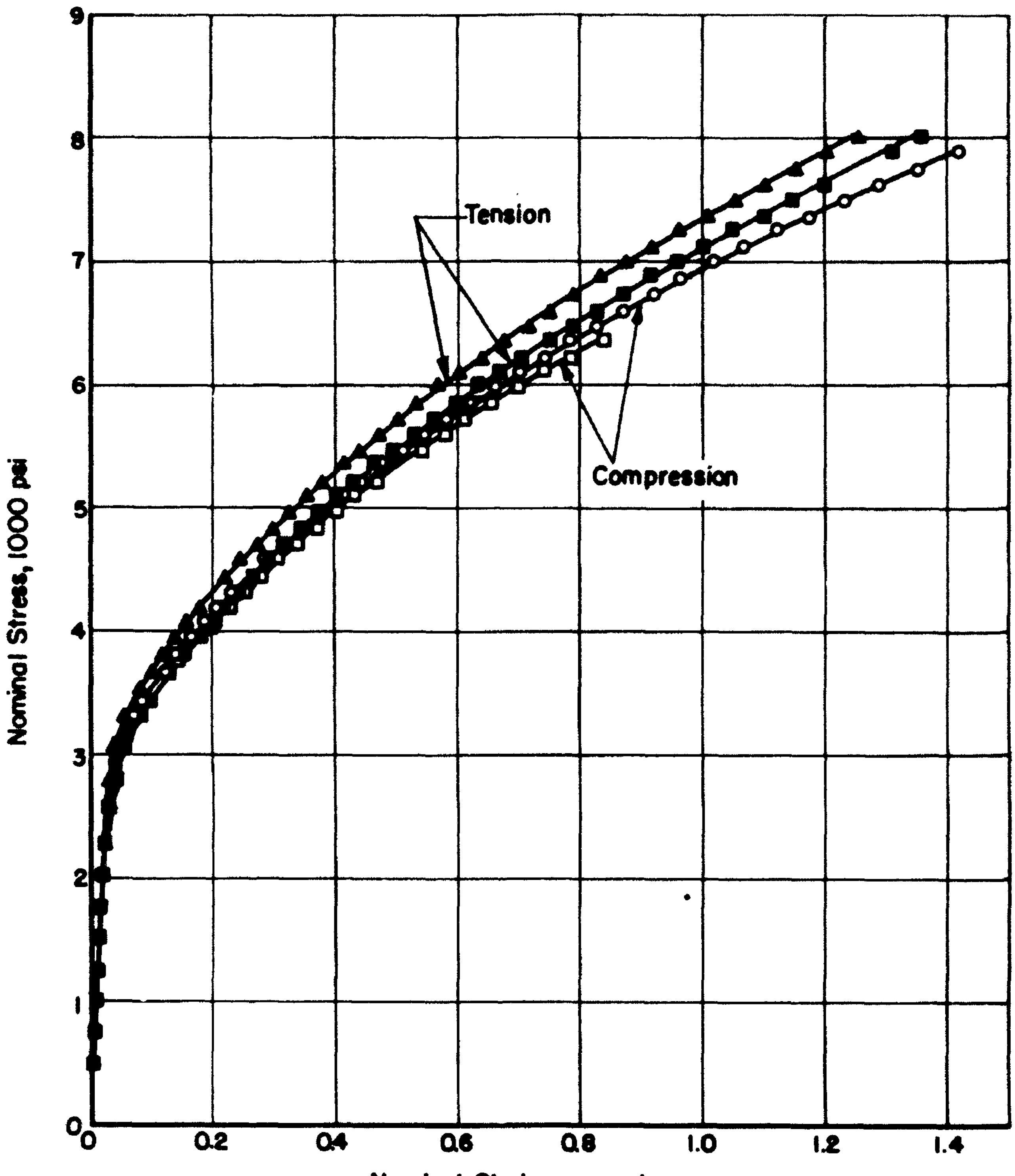

FIGURE 17. STATIC TENSION AND COMPRESSION STRESS-STRAIN CURVES FOR 1100-O ALUMINUM AT ROOM TEMPERATURE

A-16788

TABLE 12. STATIC-TENSION PROPERTIES OF 1100-0 ALUMINUM AT 300°F

Specimen Number	Modulus of Elasticity, 10^6 psi	Proportional Limit, psi	0.2% Offset Yield Stress, psi
21A	9.61	2000	3710
153A	9.20	1750	3700

TABLE 13. STATIC-COMPRESSION PROPERTIES OF 1100-0 ALUMINUM AT 300°F

Specimen Number	Modulus of Elasticity, 10^6 psi	Proportional Limit, psi	0.2% Offset Yield Stress, psi
134A	9.63	1750	3990
297A	9.79	1900	3750

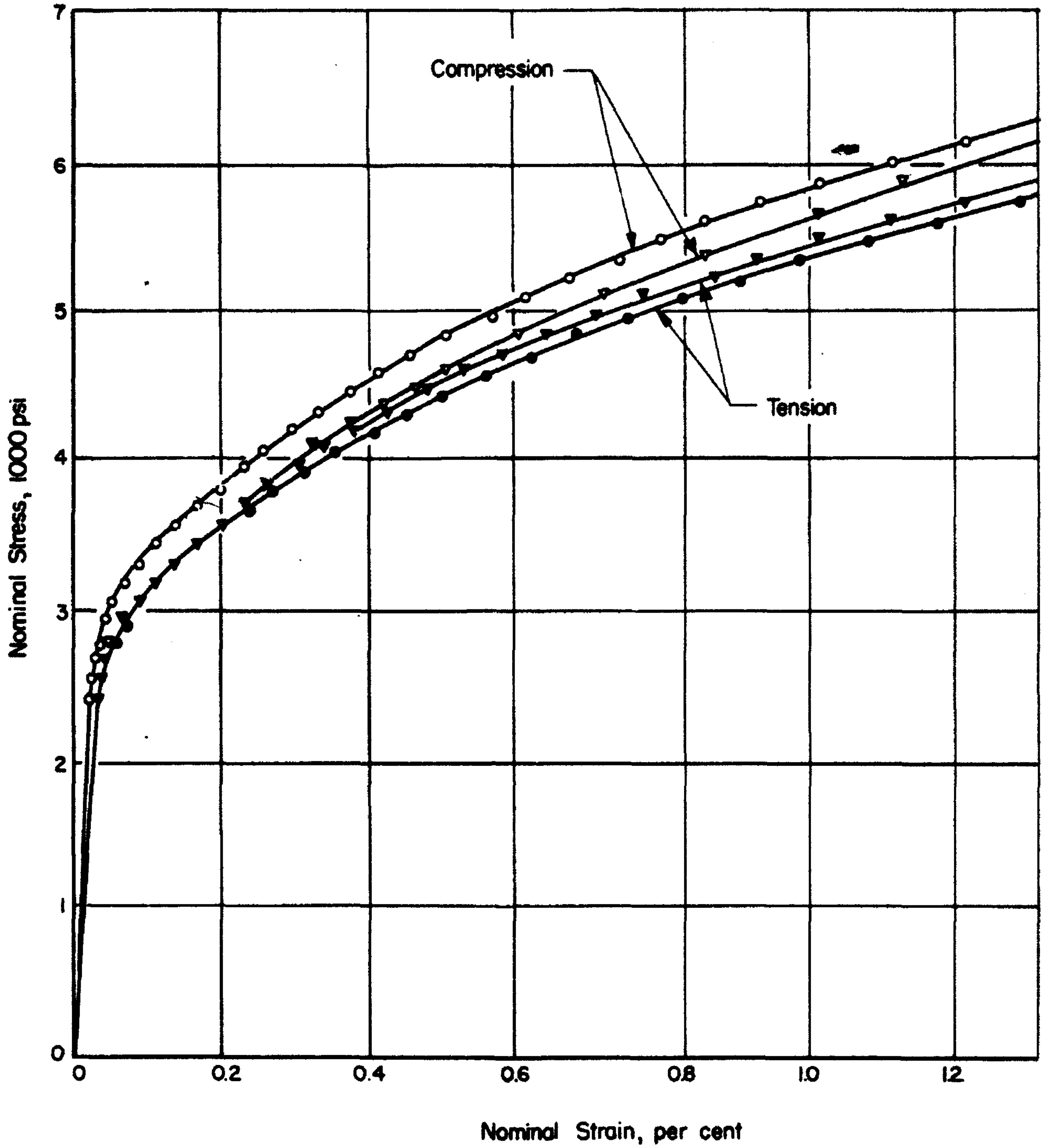

FIGURE 18. STATIC TENSION AND COMPRESSION STRESS—STRAIN CURVES FOR 1100-O ALUMINUM AT 300°F

exist, in fact, appear to be within the experimental scatter of the tests. The absence of marked differences in the static properties for the aluminum 1100-O simplifies the subsequent comparisons to be made between tension and compression creep. It suggests that, with regard to history, that is, fabrication and heat treatment, the material is in a "neutral" state.

Tension- and Compression-Creep Tests

Material units for creep specimens of 1100-O aluminum were selected according to the techniques outlined previously in this report. These specimens were machined to the same configuration as the 2024-T4 creep specimens; however, the length of the reduced section was decreased to 2 inches to prevent creep buckling in compression. The design of this specimen was shown in Figure 1. These creep specimens were given the same heat treatment prior to testing as that given to the static specimens of 1100-O aluminum. The procedures and equipment employed in tension- and compression-creep tests on 1100-O aluminum were the same as those employed in the tests on the 2024-T4 alloy.

Figure 19 gives the results of the tension- and compression-creep tests on the 1100-O aluminum at 300°F. The creep tests conducted at 2,000 psi did not produce sufficient creep strain to indicate whether or not a difference existed between tension and compression creep at that level. At a level of 3,000 psi, the 1100-O aluminum exhibited greater creep resistance in compression. The data indicated a difference in both the primary and secondary stages. This was similar to the behavior of the 2024-T4 alloy at 300°F. It should be pointed out, however, that these stresses of 2,000 psi and 3,000 psi were both greater than the proportional limit stress of this 1100-O aluminum at 300°F. The effect of the resultant plastic strains upon the subsequent creep deformation is unknown at this time; however, it appears

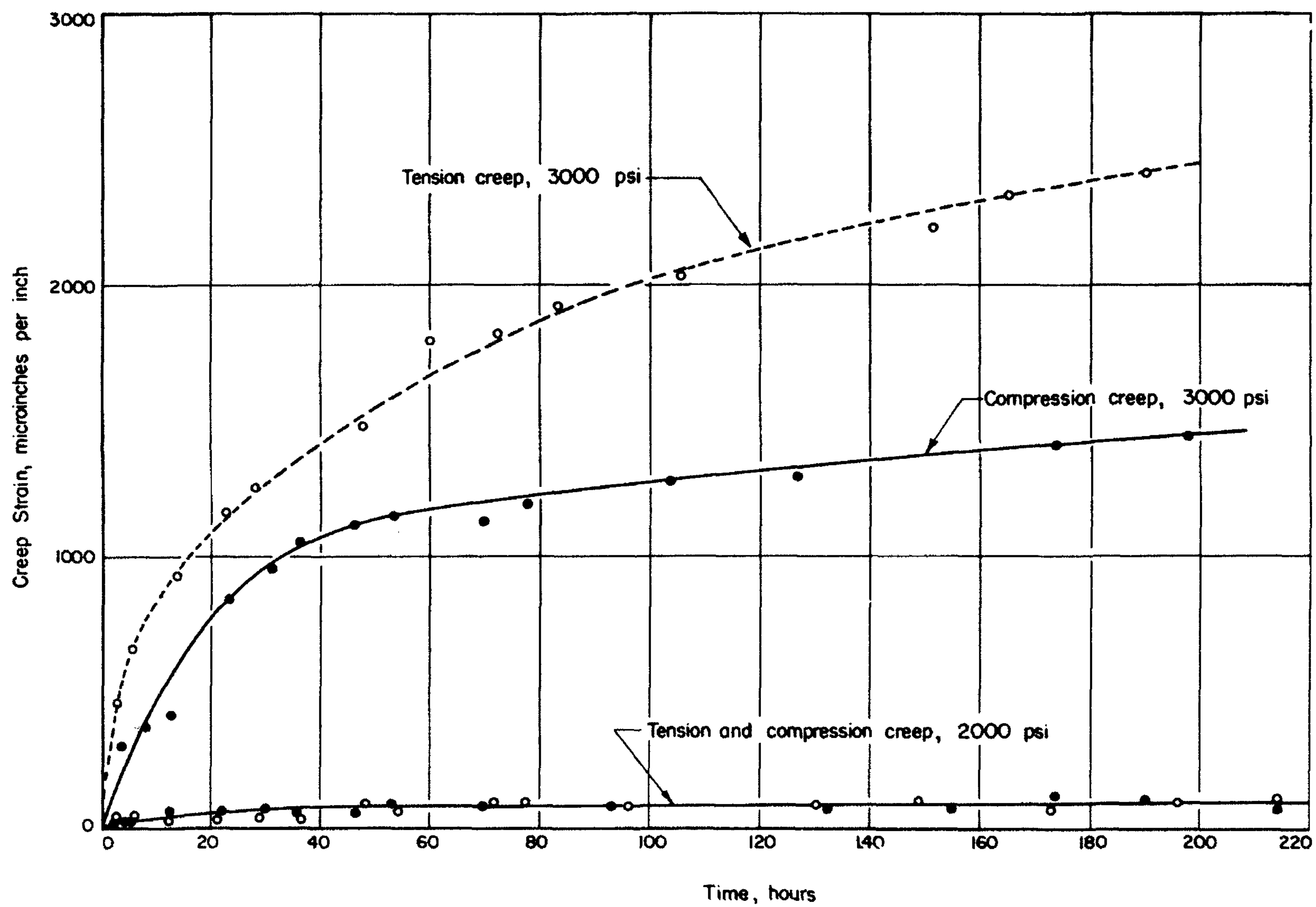

FIGURE 19. COMPARISON OF TENSION- AND COMPRESSION-CREEP CURVES FOR 1100-O ALUMINUM AT 300°F

from Figure 19 that the increase of stress from 2,000 psi to 3,000 psi created the greatest change in the creep taking place during the primary stage.

The fact that the tension-compression creep interchange at 300°F was found the same for both the 2024-T4 alloy and the 1100-0 aluminum may, of course, be simply a coincidence. However, the results do not destroy the possibility that this interchange behavior may be the reflection of a temperature phenomenon. It is quite possible that a reversal in the behavior of 1100-0 aluminum may occur at a higher temperature. Some support for this is given in studies by Servi and Grant[22] who conducted creep tests on 1100-0 aluminum at several temperatures. They observed what they termed a "break" or transition in the creep behavior which was affected by stress and temperature. For a given stress, they found that when the temperature was raised to a certain value, a change in creep behavior took place. They indicated that this transition corresponded to the "equicohesion" of the grains and grain boundaries. At this point, the grains and grain boundaries are considered to make equal contributions to the creep deformation of the specimen. Whether or not this phenomenon observed by Servi and Grant has any relation to the differences between tensile and compressive creep is unknown. Further data on 1100-0 aluminum at temperatures other than 300°F would aid in determining the effects of temperature on creep interchange.

SUMMARY AND CONCLUSIONS

Research was conducted on 1100-0 aluminum and 2024-T4 aluminum alloy. Tension- and compression-creep tests were conducted at various stress levels and temperatures in an attempt to determine whether significant differences exist between tension- and compression-creep behavior. Static tests at the same temperatures, metallographic studies, and hardness studies were used to supplement the creep data. This research has indicated the following:

1. Test equipment and techniques developed permitted the measurement of creep strain with a sensitivity of 10 microinches per inch and an estimated accuracy of ± 25 microinches per inch.
2. Significant differences exist between the tensile- and compressive-creep behavior of both 1100-0 aluminum and 2024-T4 aluminum alloy at all test temperatures (maximum temperature = 375°F). In all cases, compression-creep resistance was greater than tension-creep resistance.
3. Significant differences in both the primary and secondary stages existed between tension creep and compression creep of 2024-T4 at 300°F. Differences in creep rate in secondary-stage behavior disappeared at 375°F.
4. Comparison of data of this investigation with other data on 2024-T4 indicated that a reversal in creep interchange takes place between 375°F and 450°F. Furthermore, these data suggest that creep interchange may be a function of temperature.
5. The levelling off of certain creep curves for 2024-T4 in the region of 15 to 50 hours may be associated with age-hardening phenomena.
6. Marked differences in flow properties of 2024-T4 from different lots may be attributed largely to differences in grain size.

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